BIOMECHANICAL ANALYSIS OF FIXED BEARING AND MOBILE BEARING TOTAL KNEE PROSTHESES

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Abstract

In total knee replacement (TKR) surgery, mobile bearing (MB) total knee prostheses were designed to more closely mimic the function of the normal knee than traditional fixed bearing (FB) designs by allowing axial mobility between the polyethylene insert and tibial tray. Despite the hypothetical benefits of the MB design, few studies have objectively analysed knee biomechanics during activities of daily living (ADLs) in the laboratory compared to FB designs. This thesis aimed to substantiate the theoretical advantages of MB implantation during ADLs in the laboratory as well as during free living conditions, in addition to investigating previous claims of instability in MB knees. Sixteen patients undergoing primary unilateral total knee replacement (TKR) surgery were randomised to receive either a FB (*n*=8) or MB (*n*=8) total knee prosthesis and were tested at pre-surgery, three months post-surgery, and nine months post-surgery using three dimensional motion analysis in the laboratory and electrogoniometry and accelerometry during free living conditions. No differences were found between FB and MB groups during walking at post-surgery that could not be explained by differences at pre-surgery. There were also no differences between FB and MB groups during the more biomechanically demanding activities of stair negotiation and sit to stand and stand to sit activities, as well as no differences during free living conditions away from the laboratory. There appears to be no evidence based rationale for the widespread use of MBs with regards to optimising knee function during ADLs. This thesis was the first to compare FB and MB designs using the same implant range, posterior cruciate ligament (PCL) scenario, posterior stabilising strategy, and patella strategy over a range of ADLs, as well as being the first to combine testing in the laboratory with testing during free living conditions away from the laboratory.

List of current peer-reviewed publications arising from this thesis

Journal articles

- **Urwin SG**, Kader DF, St Clair Gibson A, Caplan N, Stewart S. Three dimensional gait analysis of fixed bearing and mobile bearing total knee prostheses during walking. Bone Joint J 2014; in press. Appendix A.

- **Urwin SG**, Kader DF, St Clair Gibson A, Caplan N, Stewart S. Do mobile bearing total knee prostheses produce instability during stair ascent? A prospective randomised study. Bone Joint J 2014; in press. Appendix B.

- **Urwin SG**, Kader DF, Caplan N, St Clair Gibson A, Stewart S. Gait analysis of fixed bearing and mobile bearing total knee prostheses during walking: Do mobile bearings offer functional advantages? Knee 2014; in press. Appendix C.

- **Urwin SG**, Kader DF, Caplan N, St Clair Gibson A, Stewart S. Validation of an electrogoniometry system as a measure of knee kinematics during activities of daily living. JMR 2013; 16(1): 1350-1360. Appendix D.

Conference proceedings

- **Urwin SG**, Kader DF, St Clair Gibson A, Caplan N, Stewart S. Three dimensional gait analysis of fixed bearing and mobile bearing total knee prostheses during stair descent. In: Proceedings of the British Association for Surgery of the Knee 2013, Leeds, UK. Appendix E

- **Urwin SG**, Kader DF, Caplan N, St Clair Gibson A, Stewart S. Validation of an Electrogoniometry System as a Measure of Knee Kinematics During Activities of Daily Living. In: Proceedings of the American Society of Biomechanics 2012, Gainesville, FL, USA. Appendix F.

- **Urwin SG**, Kader DF, St Clair Gibson A, Caplan N, Stewart S. Long term monitoring of the knee flexion angle: A spectrum analysis. In: Proceedings of the 2nd International Conference of Ambulatory Monitoring of Physical Activity and Movement 2011, Glasgow, UK. Appendix G.

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Authors declaration

I declare that the work contained within this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas, and contributions from the work of others. All experimentation has been ethically approved. Approval was sought and granted from the Faculty of Health and Life Sciences Ethics Committee and the County Durham and Tees Valley Two NHS Regional Ethics Committee, details of which are contained within the general methods of this thesis.

Name:

Signature:

Date:

List of abbreviations

ACL	Anterior cruciate ligament
ADLs	Activities of daily living
BMI	Body mass index
DOF	Degrees of freedom
FB	Fixed bearing
GRF	Ground reaction force
ICC	Intraclass correlation
KAD	Knee alignment device
LCI	Lower 95% confidence interval
LOA	Limits of agreement
MB	Mobile bearing
MDC	Minimum detectable change
NHS	National Health Service
OA	Osteoarthritis
OKS	Oxford Knee Score
PCL	Posterior cruciate ligament
ROM	Range of movement
SD	Standard deviation
SEM	Standard error of measurement
STA	Soft tissue artefact
STE	Standardised typical error
TE	Typical error
TKR	Total knee replacement
UCI	Upper 95% confidence interval
vGRF	Vertical ground reaction force

1.0 Introduction

1.1 Development of total knee prostheses

Total knee replacement (TKR) surgery has become a widely accepted method for treating severe functional limitations in the knee, such as late stage knee osteoarthritis (OA) [1, 2]. Over 70,000 primary TKR operations were performed in England and Wales in 2009 [3]. Similar utilisation rates have been reported in the United States, with a substantial increase in the last decade [4-6]. Currently, over 650,000 TKR operations are performed annually in the United States, with a projected increase to 3,480,000 by the year 2030 [5]. Recent increases in life expectancy and body weight, coupled with a current prosthesis survival range of 10 to 15 years [7], have emphasised the need for prosthesis durability and longevity [8]. The increasing prevalence of TKR surgery highlights the need for the appropriate assessment of post-operative outcome in patients [9].

There are different prosthetic designs available to orthopaedic surgeons for TKR surgery [10]. Such designs can be classified as fixed bearing (FB), or mobile bearing (MB), with the MB design encompassing the terms ‘meniscal bearing’ for the posterior cruciate ligament (PCL) retaining scenario, and ‘rotating platform’ for the PCL sacrificing scenario [11-14]. Figure 1 depicts replica models of the FB and MB prostheses used in the experimental work of this thesis, with Figure 2 illustrating how they differ mechanically.

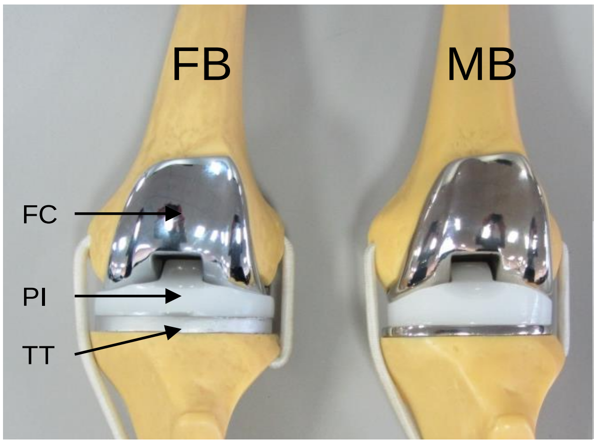

Figure 1 – The fixed bearing and mobile bearing total knee prostheses used in this thesis. FC = femoral component; PI = polyethylene insert; TT = tibial tray

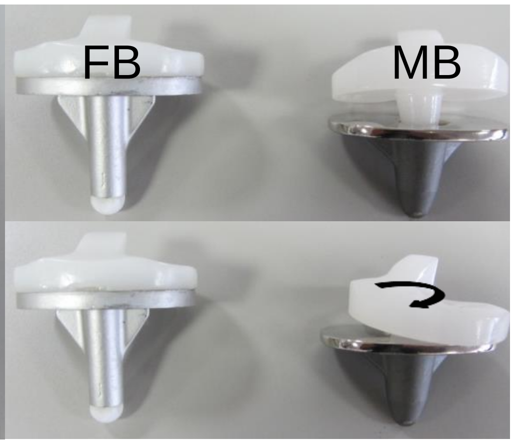

Figure 2 – The mechanical differences between the fixed bearing and mobile bearing total knee prostheses used in this thesis. The mobile bearing prosthesis is not fixed to the tibial baseplate, thus allowing axial rotation

In FB prostheses, the polyethylene insert is fixed to the tibial tray, thus constraining axial rotation (Figure 2). Figure 3 depicts an anterior view of a FB total knee prosthesis *in situ* during a TKR operation, with the prosthesis displaying no axial rotation at the bearing interface, despite the knee being flexed to approximately 90°. The potential limiting implications of this is demonstrated in the normal knee, with around 30° of axial rotation required for 120° of knee flexion [15].

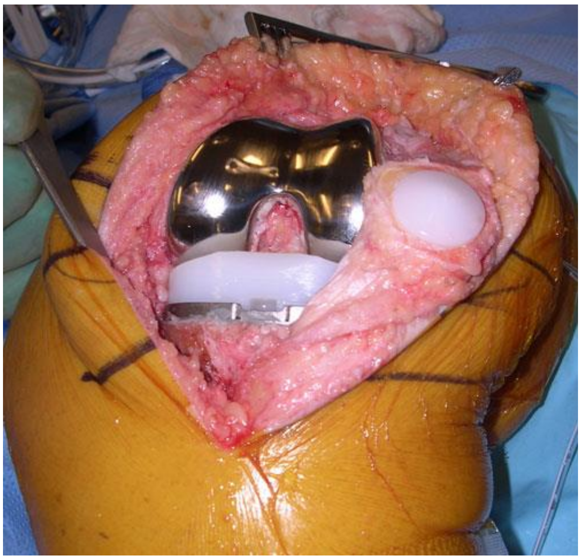

Figure 3 – An anterior view of a fixed bearing total knee prosthesis *in situ*. The image is printed with permission from the University of Washington, Orthopaedic and Sports Medicine Department, Seattle, WA, USA

Despite these mechanical deficiencies, FB designs have been found to be durable with successful long term fixation [16-18]. In a study of 101 knees, Colizza et al. [19] found good to excellent clinical results in 96.0% of patients, with a prosthesis survival rate of 96.4% after 10 to 15 years of implantation. An issue with follow-up studies due to their longitudinal study design, in particular those that were undertaken more than a decade ago, is that they typically monitor elderly patients with low activity levels [14]. Current evidence suggests that TKR patients are getting younger, with 43.6% of TKR patients in the United States under 65 years of age [3]. Such findings, coupled with evidence of increases in patient life expectancy and body weight [7], provide support for the need for increased prosthesis function, durability, and longevity [8].

Prosthesis fixation and polyethylene wear were identified as significant contributing factors to prosthesis failure in the late 1970's and early 1980's [14]. Fixed bearing prostheses with a high conformity bearing surface provide low contact stress, but initiate excessive moments at the bone-implant surface, which is a major cause of component loosening [20]. Prostheses with low conformity bearing surfaces, however, produce less constraint force, but generate high contact stresses leading to early prosthetic failure [21, 22]. This has been described as the "kinematic conflict" between low stress articulations and free rotation [14, 20, 23, 24].

These confounding factors led to the development of the MB design. The first MB prosthesis introduced was the Oxford device (Biomet, Bridgend, UK), designed and implemented over 35 years ago [25]. This was followed by the Low Contact Stress prosthesis (De Puy, Warsaw IN, USA), documented by Rose et al. [26] in 1983. In current MB prostheses, some designs allow both antero-posterior translation and internal-external rotation, whilst other designs are constrained to internal-external rotation at the bearing interface [27].

1.2 Theoretical basis for mobile bearing total knee prostheses and rationale for further research

Mobile bearing prostheses were designed to mimic the function of the meniscus by accommodating the natural combination of rolling and sliding movements [28], and as a result, facilitate planar rotation about the vertical axis of the femur [29, 30]. Dual surface articulation at both the superior and inferior surfaces of the polyethylene insert promotes load sharing between the relative displacement of the tibial and femoral components, dissipating knee moments and shear forces to the surrounding soft tissues in a similar manner to the normal knee [14]. As a result, this is postulated to reduce sub-surface stress [31-35].

A reduction in sub-surface stress was found to contribute to early findings of decreased wear associated with polyethylene failure in MB prostheses after TKR surgery [28, 36-40]. A further theoretical advantage, from the findings of Buechel et al. [41], suggests that MB designs can tolerate slight femoral and tibial rotation implantation errors without adverse effects on patellar tracking. Other potential advantages include greater fixation of the prosthesis to the bone, thus decreasing the risk of component loosening due to the unconstrained movement of the insert uncoupling forces generated at the prosthesis-bone interface [20]. The fundamental aim of MB implantation is to achieve stable long term fixation with minimal generation of polyethylene wear and subsequent osteolysis [42-46].

Despite these proposed advantages, many theoretical benefits of the MB design have yet to be substantiated, with numerous authors documenting no improvements in questionnaire based functional outcomes when compared to FB designs over the past decade [2, 31, 47-58]. Further, such claims of improved functional rotation, stability, and reduced wear, remain controversial [59], with many theoretical claims not supported by the peer reviewed literature [33, 60-62].

The majority of studies assessing the function of MB prostheses have used questionnaires. These data, although useful, are subject to individual perspective and do not provide an objective measure of lower limb function [63]. Fluoroscopic analyses have also been used to obtain *in vivo* three dimensional knee kinematics in TKR patients [34, 43, 64-70]. Fluoroscopy can provide an accurate measure of *in vivo* knee kinematics; although natural patterns of displacement can become inhibited due to the small field of view [71], in addition to exposing patients to unnecessary ionising radiation [72].

Gait analysis is a noninvasive tool that is not restricted to the dimensions of fluoroscopic analyses, and can be used to measure functional outcome following TKR surgery [9]. Current three dimensional motion analysis systems are able to calculate kinematics and kinetics about the knee to a high degree of accuracy, establishing gait analysis as an important tool in the clinical management of knee problems [73]. As knee motion has a direct impact on patient function [74-76], it is important to further examine the lower limb biomechanics of patients implanted with MB prostheses in light of potential functional advantages due to the axial mobility of the polyethylene insert.

Little research has directly compared FB and MB prostheses by means of gait analysis to determine the comparative functional performance during common activities of daily living (ADLs). From the available literature [10, 29, 77-80], it was found that MB prostheses provided greater knee flexion during the stance [78] and swing phases [80] of walking than FBs. These previous limited findings of increased range of movement (ROM) provide support for the theoretical benefits of MBs [14], although further work is required to substantiate this evidence as only a small number of patients were assessed in these studies, in addition to a number methodological limitations that question the validity of the findings.

More concerning previous results have shown MB prostheses to exhibit reduced external knee extension and adduction moments during stair ascent gait compared to FB designs [29, 79]. The combination of a reduction in external knee extension and adduction moments suggests the presence of lower limb compensatory mechanisms. This provides evidence of a protective knee pattern during demanding ADLs due to potential instability, although further work is required to substantiate this evidence as only a small number of patients were assessed in these studies, in addition to a number methodological limitations that question the validity of the findings. Throughout the entirety of this thesis, all subsequent mention of external moments will be abbreviated to ‘moments’.

An approach complementary to traditional gait analyses is to monitor function as the patient goes about normal daily activity [81]. Halstead [81] proposed that continuous, remote, and unobtrusive monitoring provides a more useful means of evaluating the success of rehabilitation than specific testing in highly controlled and standardised settings. As a result, it has been suggested that laboratory testing may not always be clinically valid as it is not exclusively representative of everyday living [82]. Due to this, problems can arise when extrapolating the results for interpretation outside of the laboratory.

It is currently unknown what the spectrum of movement is at the knee joint in TKR patients during everyday living, and whether the axial mobility of the polyethylene insert in MBs allow increased ROM at the knee for longer periods of time. It is also unknown whether differences between pre-surgery and post-surgery occur within prosthesis groups, suggesting potentially improved rehabilitation in one design over the other. Better understanding of the influence of design parameters on biomechanics is important for improving current total knee prostheses in order to achieve greater knee joint stability, mobility, and load-bearing capacity [83, 84]. This is of heightened importance due to the findings of Kurtz et al. [3] which suggest a growing population of younger patients who will require not only an implant to function for at least two decades, but also one that is adapted to the higher physical demands of the younger patient.

1.3 Aims of this thesis

In light of these issues, the primary aim of this thesis was to examine whether implantation with MBs offer biomechanical advantages over FB designs during ADLs in the laboratory using three dimensional motion analysis, but also during free living conditions away from the laboratory using electrogoniometry and accelerometry. As a secondary aim, the previous limited findings of compensatory mechanisms due to instability in MB designs were assessed.

1.4 Objectives of this thesis

In order to achieve the aims of this thesis, the following objectives were devised:

- To critically analyse previous literature to inform the conceptual and experimental approach to gait analysis.

- To assess the reliability of the gait laboratory data to aid the interpretation of the inferential statistical analyses in the comparison of FB and MB total knee prostheses.
- To analyse FB and MB total knee prostheses during walking, a fundamental ADL.
- To analyse FB and MB total knee prostheses during stair negotiation, sit to stand, and stand to sit activities to determine whether differences are apparent during more biomechanically demanding ADLs.
- To determine the validity and reliability of an electrogoniometry and accelerometry system for testing during free living conditions away from the laboratory to ensure appropriate and valid use of the systems.
- To further analyse FB and MB total knee prostheses during free living conditions away from the laboratory as laboratory testing may not always be entirely representative of true functional ability.

1.5 Synopsis of this thesis

- **Chapter 2** describes a systematic literature review and meta-analysis of literature comparing FB and MB total knee prostheses by means of gait analysis during ADLs.
- The general methods for this thesis are outlined in **Chapter 3**, with detail relating to instrumentation set-up, protocols, data processing, and data analysis.
- **Chapter 4** comprises a within-session and between-session reliability assessment using three dimensional motion analysis.
- **Chapter 5** analyses the lower limb biomechanics of patients implanted with FB and MB prostheses during walking.
- Lower limb biomechanics between prosthesis groups are further analysed in **Chapter 6** during stair negotiation, sit to stand, and stand to sit activities.
- **Chapter 7** presents a validation and reliability study of the electrogoniometry and accelerometry systems.
- **Chapter 8** applies these systems in the analysis of knee kinematics and physical activity for the comparison of FB and MB implanted patients during free living conditions away from the laboratory.

- **Chapter 9** provides a general discussion of the work presented in this thesis.

2.0 Literature review

2.1 Introduction

The aim of this chapter was to retrieve articles comparing fixed bearing (FB) total knee prostheses to mobile bearing (MB) designs by means of gait analysis, in addition to analysing the collated literature to inform the main experimental work of this thesis. A systematic approach was used to optimise retrieval of relevant literature, with a meta-analysis undertaken for cross study comparisons.

2.2 Method

2.2.1 Literature search strategy

An initial search of the literature was completed in January 2011, with an updated search in June 2013, for articles comparing FB and MB total knee prostheses by means of gait analysis. Medline (PubMed), The Cochrane Library, Cinahl, and Embase were searched for full text studies published in English. The electronic database searches were complemented by cross-checking citations from pertinent articles. Combinations and variations of the following terms were used within the searches: ‘fixed bearing’, ‘mobile bearing’, ‘rotating platform’, ‘total knee replacement (TKR)’, ‘total knee arthroplasty’, ‘gait analysis’, ‘motion analysis’, ‘walking’, ‘activities of daily living’, ‘functional activities’, ‘spatiotemporal’, ‘kinematic’, and ‘kinetic’. The search yielded an initial 1267 studies.

2.2.2 Study selection criteria

To be included within the review, studies had to assess patients with implanted FB and MB total knee prostheses using gait analysis only, or via a combination of assessment tools including gait analysis. Studies investigating any functional activity were accepted into the final review. In addition, studies had to present original raw data, including spatiotemporal, kinematic, or kinetic variables of the knee during experimental trials. Studies that did not present original raw data were excluded from the review, of which there were none. Studies were also excluded if the gait analysis was undertaken less than six months post-surgery to allow an appropriate duration of rehabilitation, of which there were none. Due to the variability of the previously examined gait analysis literature [9], studies were included regardless of further methodological criteria; for instance, the comparison of patient data to a control group. This was undertaken to maximise potential findings from the review.

Following the retrieval of the initial literature, irrelevant and duplicate articles were discarded by reading the title. Abstracts were read of pertinent titles and the full texts accessed of potentially relevant studies from information presented in the abstract. Six studies were then analysed for satisfaction of the inclusion criteria after Mockel et al. [78] was excluded as the full text was not available in English. Five studies remained for further analysis after Jolles et al. [85] was excluded as no comparable variables were presented which would have contributed to the collated findings of this review.

2.2.3 Methodological quality

No randomised controlled studies were available for review due to the nature of the research. A validated checklist developed by Downs and Black [86] for the assessment of methodological quality was used to assess the quality of the studies. The checklist, which comprised 27 constructs, has been shown to have good inter-rater and intra-rater reliability [86], as well as good correlation with existing methodological quality checklists when applied to randomised controlled studies [87].

2.2.4 Data analysis

A meta-analysis was performed using MetaAnalyst (Version 3.1, Medford, MA, USA) [88] to examine pooled differences between TKR groups (FB or MB) and controls. Variables were only entered into the meta-analysis where three or more studies reported TKR and control data for the specific variable. Individual and overall effect sizes (Cohen's *d*), 95% confidence intervals, and the I^2 statistic were calculated. Heterogeneity of the studies included in the meta-analysis was examined using the I^2 statistic in order to determine the validity of inferring the findings of the meta-analysis to the wider population. The degree of heterogeneity was assumed as low, moderate or high, according to I^2 being 25%, 50% or 75%, respectively [89].

2.3 Results

2.3.1 Assessment of methodological quality

Table 1 summarises the methodological quality of the five studies retrieved from the literature. Specific constructs of the Downs and Black [86] criteria were selected where relevant to the included studies.

Table 1 – Assessment of the methodological quality of the five included studies that passed scientific scrutiny in a systematic procedure of literature identification. The Downs and Black criteria [86] was used with criteria selected that were specific to the studies

Study	Downs and Black [86] criteria										
	1	2	3	5	6	7	12	16	18	25	27
Catani [29]	Y	Y	Y	N	Y	Y	N	Y	Y	N	N
Fantozzi [79]	Y	Y	Y	N	Y	Y	N	Y	Y	N	N
Kramers-de Quervain [80]	N	Y	Y	N	Y	Y	N	Y	Y	N	N
Sosio [77]	Y	Y	Y	N	Y	Y	N	Y	Y	N	N
Tibesku [10]	Y	Y	Y	Y	Y	Y	N	Y	Y	N	N

-'Y' equates to 'Yes, the study included the relevant criterion'
- 'N' to 'No, the study did not include the relevant criterion'
- Item numbers:
'No.1' – Clear aim
'No.2' – Outcomes described
'No.3' – Patients described
'No.5' – Confounders described
'No.6' – Main findings clearly described
'No.7' – Measures of random variability
'No.12' – Subjects represent population
'No.16' – Planned analysis
'No.18' – Appropriate statistics
'No.25' – Adjustments for confounders
'No.27' – Power calculation

All studies satisfied a similar number of criteria across the rating constructs, with Kramers-de Quervain et al. [80] differing from Catani et al. [29], Fantozzi et al. [79], Sosio et al. [77], and Tibesku et al. [10] in that the study did not present a clear aim. Other differences were observed in items 'No.5' and 'No.10', with Tibesku et al. [10] not providing a description of potential confounding variables.

All five studies compared FB and MB prostheses, although there were differences in the research questions. Kramers-de Quervain et al. [80] examined whether it was possible to compare functional activity using gait analysis in two different prosthetic designs implanted bilaterally. Fantozzi et al. [79] utilised both gait analysis and fluoroscopic analysis to verify whether TKR kinematic characteristics can be correlated to full body kinematic and kinetic variables. Catani et al. [29], Sosio et al. [77], and Tibesku et al. [10] compared the functional performance of FB and MB total knee prostheses using gait analysis, with Catani et al. [29] investigating stair ascent and descent, Sosio et al. [77] level walking and squatting, and Tibesku et al. [10] level walking.

2.3.2 Study design and patient characteristics

Selected study design components of the included studies are summarised in Table 2. Discrepancies were evident across the study design of the five studies when combined. Kramers de-Quervain et al. [80] did not report whether the prostheses were posterior stabilised, or whether the posterior cruciate ligaments (PCL) were retained or sacrificed. Catani et al. [29] reported the FB design, but failed to specify the configuration of the MB design. Tibesku et al. [10] was the only study that used the same component design for both the FB and MB prostheses, utilising a PCL retaining configuration in both prostheses.

Only Catani et al. [29] stated the number of surgeons that performed the TKR procedure. Kramers-de Quervain et al. [80] included entirely bilateral TKR patients whom had undergone implantation in each leg within two years. Both Catani et al. [29] and Sosio et al. [77] included only unilateral TKR patients, however, neither study specified whether bilateral patients were excluded.

Moderate sample sizes were evident across the five studies (Table 3), with a mean of 10.0 ±4.42 patients in the FB groups, and a mean of 10.2 ±3.96 patients in the MB groups. There were also differences in the mean and range of time after surgery that the gait analyses were undertaken, with Sosio et al. [77] and Tibesku et al. [10] failing to report this. Catani et al. [29] presented large differences between the mean FB (11 months) and MB (20 months) gait analysis time after surgery. The greatest range was observed in Kramers-de Quervain et al. [80], with the testing of five participants between 24 and 60 months post-surgery. Catani et al. [29], Fantozzi et al. [79], and Kramers-de Quervain et al. [80] reported ranges of gait analysis duration after surgery, but did not report the distribution about the mean.

Only Tibesku et al. [10] reported the proportion of patients with osteoarthritis (OA) or rheumatoid arthritis, as well as reporting whether the exclusion of patients with rheumatologic conditions was undertaken. Catani et al. [29] and Sosio et al. [77] excluded patients with signs of implant loosening. Kramers de-Quervain et al. [80] and Tibesku et al. [10] excluded patients with additional pathologies affecting gait, although Kramers-de Quervain et al. [80] did not specifically state what these were. Fantozzi et al. [79] did not state any inclusion or exclusion criteria.

Table 2 – Study design components of the five included studies that passed scientific scrutiny in a systematic procedure of literature identification

Design component	Catani [29]	Fantozzi [79]	Kramers-de Quervain [80]	Sosio [77]	Tibesku [10]
Prosthetic manufacturer					
FB:	Insall Burstein, Zimmer, USA	Optetrak, Exactech, USA	GSB[§], Allopro, Sulza Medica, Switzerland	Multigen, Italy	Genesis II, Smith and Nephew, Germany
MB :	MBK prosthesis, Zimmer, USA	Interax ISA, Stryker, USA /Howmedica/Ostetonics, USA	LCS, De Puy, USA	Multigen, Italy	Genesis II, Smith and Nephew, Germany
Design					
FB:	Posterior stabilised.	Posterior stabilised.	NR	Posterior stabilised	PCL retaining
MB:	NR	PCL retaining	NR	PCL retaining	PCL retaining
No. of surgeons	1	NR	NR	NR	NR
Bilateral TKR patient inclusion percentage†	0	5	100	NR	NR
No. of OA/RA inclusion percentage	NR	NR	NR	NR	NR

[§]Semiconstrained loose hinged prosthesis; [†] Patients involved in analysis; 'OA/RA' to 'Osteoarthritis/rheumatoid arthritis; 'NR' to 'Not reported'

Table 3 – Patient characteristics of the five included studies that passed scientific scrutiny in a systematic procedure of literature identification

Patient information	Catani [29]		Fantozzi [79]		Kramers-de Quervain [80]	Sosio [77]		Tibesku [10]	
	FB	MB	FB	MB	Bilateral	FB	MB	FB	MB
No. of Patients (initial)	10	10	10	11	5	8	9	17	16
Male	2	2	1	3	1	1	0	5	7
Female	8	8	9	8	4	7	9	12	9
Mean height: m (SD)	1.58	1.57	1.57	1.62	1.65	NR	NR	NR	NR
Mean mass: kg (SD)	82.0	75.0	67.5	80.8	87.5	NR	NR	NR	NR
Mean age: yrs (SD)	68.0	71.0	65.7	74.3	75.4	75.5 (2.80)	72.0 (5.50)	66.0 (10.0)	65.0 (9.00)
Mean GA after surgery: months (range)	11 (8-16)	20 (14-26)	21.5 (9-52)	21.9 (11-35)	(24-60)	NR	NR	NR	NR
No. OA/RA patients	NR	NR	NR	NR	NR	NR	NR	All OA	All OA
Patella	RS	RS	NR	NR	NR	Not RP	Not RP	Not RS	Not RS

'SD' equates to 'Standard deviation'; 'GA' to 'Gait analysis'; 'RA' to 'Rheumatoid arthritis'; 'RS' to 'Resurfaced'; 'RP' to 'Replaced'; 'NR' to 'Not reported'; 'N/A' to 'Not applicable'

2.3.3 Gait analysis variables

2.3.3.1 Spatiotemporal data

Only gait velocity was reported across all five studies (excluding the squatting activity in Sosio et al. [77], which was not applicable in this instance), with three studies [10, 29, 79] reporting double support duration (Table 4). Catani et al. [29], Fantozzi et al. [79], and Kramers-de Quervain et al. [80] were the only studies that undertook statistical analyses comparing FB and MB prostheses across the spatiotemporal variables. Fantozzi et al. [79] found the MB group ambulated with a reduced (p<0.0005) mean velocity (27.5cm/s) than the FB group (35.6cm/s) during stair ascent. No differences, however, were observed between stance phase and double support phase duration. During stair descent, Catani et al. [29] found the MB group to have an increased (p=0.0004) double support duration (29.9 ±10.40%stride) compared to the FB group (22.5 ±4.50%stride). No trend was observed across the spatiotemporal outcome measures.

2.3.3.2 Kinematic data

Maximum knee flexion in stance and swing were reported by all five studies (Table 5), excluding stair descent in Catani et al. [29] in which maximum knee extension was reported, and squatting in Sosio et al. [77] where it was not applicable. Across the five studies and activities, statistical analyses between FB and MB prostheses were undertaken in 13 variables, with only two reaching significance. Kramers-de Quervain et al. [80] found that the MB side had a greater (p=0.04) maximum knee flexion in swing (52.4 ±7.56°) than the FB side (47.1 ±4.74°) during walking. Fantozzi et al. [79] described contrasting findings, reporting that patients implanted with a MB prosthesis ascended with reduced (p=0.022) knee range of movement (ROM) in stance phase (46.6 ±7.30°) than FB patients (51.5 ±6.70°) during stair ascent. No trend was observed across the kinematic variables.

Table 4 – Spatiotemporal reported variables of the five included studies that passed scientific scrutiny in a systematic procedure of literature identification

Spatiotemporal variables	Level walking			Stair ascent		Stair descent
	Kramers-de Quervain [80]	Sosio [77]	Tibesku [10]	Catani [29]	Fantozzi [79]	Catani [29]
Gait velocity	***NS***	MB↑	MB↑	MB↑	***FB*↑**	FB↑
Step length	NR	NR	FB↑	NR	NR	NR
Step width	NR	NR	MB↑	NR	NR	NR
Stance phase duration	NR	MB↑	ND	FB↑	***NS***	MB↑
Swing phase duration	NR	NR	ND	MB↑	NR	FB↑
Single support duration	NR	NR	MB↑	NR	NR	NR
Double support duration	NR	NR	FB↑	FB↑	***NS***	***MB*↑**

FB*↑/MB*↑' equates to 'FB or MB group is significantly greater in the relevant parameter at the 0.05 level'; '***NS***' to 'No significant difference between FB and MB groups'; 'FB↑' or 'MB↑' to 'An indication of whether the mean of the FB and MB group was greater in the relevant variable in the absence of statistical comparison'; 'NR' to 'Not reported'; 'ND' to 'No difference between the means of the FB and MB groups when no statistical comparison was presented'

Table 5 – Kinematic reported variables of the five included studies that passed scientific scrutiny in a systematic procedure of literature identification

Kinematic variables	Level walking			Stair ascent		Stair descent
	Kramers-de Quervain [80]	Sosio [77]	Tibesku [10]	Catani [29]	Fantozzi [79]	Catani [29]
Hip flex (max)	NR	NR	FB↑	NR	NR	NR
Hip flex (min)	NR	NR	MB↑	NR	NR	NR
Hip flex (range)	MB↑	NR	FB↑	NR	NR	NR
Knee flex (max)	NR	NR	NR	NR	NR	NR
Knee flex (min)	NR	NR	FB↑	NR	NR	NR
Knee flex (max stance)	***NS***	MB↑	FB↑	***NS***	***NS***	NR
Knee flex (max swing)	***MB*↑**	MB↑	FB↑	***NS***	***NS***	NR
Knee flex (ROM stance)	***NS***	NR	MB↑	NR	***FB*↑**	NR
Knee flex (ROM swing)	***NS***	NR	MB↑	NR	NR	NR
Knee flex (sagittal ROM)	NR	NR	NR	***NS***	NR	***NS***
Knee ext (max stance)	NR	NR	NR	NR	NR	***NS***
Knee ext (max swing)	NR	NR	NR	NR	NR	***NS***
Ankle plantar flexion (max)	NR	NR	MB↑	NR	NR	NR
Ankle plantar flexion (max stance)	NR	MB↑	NR	NR	NR	NR
Ankle flexion (ROM)	NR	NR	FB↑	NR	NR	NR
Ankle dorsi flexion (max)	NR	NR	FB↑	NR	NR	NR
Ankle dorsi flexion (max stance)	NR	MB↑	NR	NR	NR	NR

FB*↑/MB*↑' equates to 'FB or MB group is significantly greater in the relevant parameter at the 0.05 level'; '***NS***' to 'No significant difference between FB and MB groups'; 'FB↑' or 'MB↑' to 'An indication of whether the mean of the FB and MB group was greater in the relevant variable in the absence of statistical comparison'; 'NR' to 'Not reported'

2.3.3.3 Kinetic data

None of the 14 reported kinetic variables were commonly reported across the five studies (Table 6). Catani et al. [29], Fantozzi et al. [79], Sosio et al. [77], and Tibesku et al. [10] all reported maximum knee flexion moments. Sosio et al. [77] did not report values, but rather the gait cycle percentage at which the maximum moment was observed. Catani et al. [29] and Fantozzi et al. [79] both reported maximum knee adduction moments, with Tibesku et al. [10] reporting maximum knee abduction moments.

Catani et al. [29] and Fantozzi et al. [79] were the only studies to present statistical analyses of kinetic variables between FB and MB groups. No differences were observed in maximum knee flexion moments during stair ascent and stair descent. Fantozzi et al. [79] found a greater (p=0.02) maximum knee extension moment in the FB group (-2.90 ±1.60%BW*Ht) when compared to the MB group during stair ascent (-1.90 ±1.20%BW*Ht). Catani et al. [29] and Fantozzi et al. [79] also found reduced (p=0.002 [29]; p=0.002 [79]) maximum knee adduction moments in MB groups (-1.90 ±1.10%BW*Ht [29]; -1.80 ±0.60%BW*Ht [79]) when compared to FB groups (-2.90 ±0.70%BW*Ht [29]; -2.70 ±1.20%BW*Ht [79]) during stair ascent.

Table 6 – Kinetic reported variables of the five included studies that passed scientific scrutiny in a systematic procedure of literature identification

Kinetic variables	Level walking			Stair ascent		Stair descent
	Kramers-de Quervain [80]	Sosio [77]	Tibesku [10]	Catani [29]	Fantozzi [79]	Catani [29]
Hip abduction moment (max)	NR	NR	FB↑	NR	NR	NR
Knee flex moment (max)	NR	NR	FB↑	***NS***	***NS***	***NS***
Knee ext moment (max)	NR	NR	NR	***NS***	***FB***↑	***FB***↑
Knee abduction moment (max)	NR	NR	MB↑	NR	NR	NR
Knee adduction moment (max)	NR	NR	NR	***FB***↑	***FB***↑	***NS***
Ankle plantar flexion moment (max)	NR	NR	MB↑	NR	NR	NR
Vertical GRF	NR	NR	ND	NR	NR	NR
Fz2n: 1st vertical peak	FB↑	NR	NR	NR	NR	NR
Fz3n: Mid-stance through	FB↑	NR	NR	NR	NR	NR
Fz4n: 2nd vertical peak	MB↑	NR	NR	NR	NR	NR
Loading rate	MB↑	NR	NR	NR	NR	NR
Unloading rate	MB↑	NR	NR	NR	NR	NR
Impulse	MB↑	NR	NR	NR	NR	NR
Medio-lateral force rate	FB↑	NR	NR	NR	NR	NR

FB*↑/MB*↑' equates to 'FB or MB group is significantly greater in the relevant parameter at the 0.05 level'; '***NS***' to 'No significant difference between FB and MB groups'; 'FB↑' or 'MB↑' to 'An indication of whether the mean of the FB and MB group was greater in the relevant variable in the absence of statistical comparison'; 'NR' to 'Not reported'

2.3.4 Cross study comparisons

Kramers-de Quervain et al. [80] and Tibesku et al. [10] were excluded from the meta-analysis as no control data were reported. Table 7 presents the cross study comparisons of FB and MB prostheses when compared to the reported control data for gait velocity (m/s).

Table 7 – Fixed bearing (FB) and mobile bearing (MB) comparisons to control participants in gait velocity (m/s) in the three studies included in the meta-analysis. Negative values suggest that the patient group ambulates with decreased gait velocity than controls. Positive values suggest that the patient group ambulates with increased gait velocity than controls

Study	Cohen's *d*	95% confidence interval		Weighting	I^2
FB					
Overall	**-1.29**	**-1.79**	**-0.78**	N/A	**0.00%**
Sosio [77] (level walking)	-2.09	-3.34	-0.84	0.16	N/A
Catani [29] (stair ascent)	-1.50	-2.51	-0.50	0.25	N/A
Fantozzi [79] (stair ascent)	-1.01	-1.95	-0.08	0.29	N/A
Catani [29] (stair descent)	-0.93	-1.85	0.00	0.30	N/A
MB					
Overall	**-1.61**	**-2.29**	**-0.94**	N/A	**36.7%**
Sosio [77] (level walking)	-1.85	-3.05	-0.65	0.20	N/A
Catani [29] (stair ascent)	-1.23	-2.19	-0.27	0.30	N/A
Fantozzi [79] (stair ascent)	-2.65	-3.88	-1.42	0.19	N/A
Catani [29] (stair descent)	-1.07	-2.01	-0.12	0.32	N/A

Combined FB and MB groups ambulated with decreased gait velocity than controls across level walking, stair ascent, and stair descent (-1.45; UCI=-2.04; LCI=-0.86) (Table 7). No differences outside of the 95% confidence levels were found between FB and MB groups. Cross study comparisons of stance phase duration (% stride) are displayed in Table 8.

Table 8 – Fixed bearing (FB) and mobile bearing (MB) comparisons to control participants in stance phase duration (% stride) in the three studies included in the meta-analysis. Negative values suggest that the patient group ambulates with decreased stance phase duration than controls. Positive values suggest that the patient group ambulates with increased stance phase duration than controls

Study	Cohen's *d*	95% confidence interval		Weighting	I^2
FB					
Overall	**1.27**	**0.77**	**1.77**	N/A	**0.00%**
Sosio [77] (level walking)	1.07	0.01	2.13	0.22	N/A
Catani [29] (stair ascent)	1.21	0.25	2.17	0.27	N/A
Fantozzi [79] (stair ascent)	1.62	0.60	2.65	0.24	N/A
Catani [29] (stair descent)	1.18	0.22	2.13	0.27	N/A
MB					
Overall	**1.06**	**0.57**	**1.54**	N/A	**0.00%**
Sosio [77] (level walking)	1.07	0.02	2.13	0.21	N/A
Catani [29] (stair ascent)	0.92	-0.01	1.84	0.27	N/A
Fantozzi [79] (stair ascent)	1.42	0.42	2.41	0.24	N/A
Catani [29] (stair descent)	0.88	-0.04	1.80	0.28	N/A

Combined FB and MB groups ambulated with increased stance phase duration than controls across level walking, stair ascent, and stair descent (1.17; LCI=0.67; UCI=1.66) (Table 8). No differences outside of the 95% confidence levels were found between FB and MB groups. Cross study comparisons of maximum knee flexion at heel contact (°) are displayed in Table 9.

Table 9 – Fixed bearing (FB) and mobile bearing (MB) comparisons to control participants in maximum knee flexion at heel contact (°) in the three studies included in the meta-analysis. Negative values suggest that the patient group ambulates with decreased maximum knee flexion at heel contact than controls. Positive values suggest that the patient group ambulates with increased maximum knee flexion at heel contact than controls

Study	Cohen's *d*	95% confidence interval		Weighting	I^2
FB					
Overall	**-1.54**	**-3.30**	**0.21**	N/A	**86.6%**
Sosio [77] (level walking)	0.12	-0.86	1.10	0.42	N/A
Catani [29] (stair ascent)	-2.55	-3.76	-1.34	0.28	N/A
Fantozzi [79] (stair ascent)	-2.28	-3.43	-1.13	0.31	N/A
MB					
Overall	**-1.14**	**-3.40**	**1.11**	N/A	**91.8%**
Sosio [77] (level walking)	1.08	0.02	2.14	0.37	N/A
Catani [29] (stair ascent)	-1.87	-2.94	-0.80	0.36	N/A
Fantozzi [79] (stair ascent)	-2.68	-3.92	-1.44	0.27	N/A

No differences outside of the 95% confidence intervals in maximum knee flexion at heel contact were found between combined FB and MB groups and controls across level walking and stair ascent (Table 9). There was a difference in the studies analysing stair ascent, with the combined FB and MB groups stair ascending with reduced maximum knee flexion at heel contact than controls (-2.28; UCI=-3.43; LCI=-1.12). No differences outside of the 95% confidence levels were found between FB and MB groups. Cross study comparisons of maximum knee flexion in swing (°) are displayed in Table 10.

Table 10 – Fixed bearing (FB) and mobile bearing (MB) comparisons to control participants in maximum knee flexion in swing (°) in the three studies included in the meta-analysis. Negative values suggest that the patient group ambulates with decreased maximum knee flexion in swing than controls. Positive values suggest that the patient group ambulates with increased maximum knee flexion in swing than controls

Study	Cohen's *d*	95% confidence interval		Weighting	I^2
FB					
Overall	**-1.33**	**-1.91**	**-0.74**	N/A	**0.00%**
Sosio [77] (level walking)	-1.17	-2.24	-0.10	0.30	N/A
Catani [29] (stair ascent)	-1.57	-2.59	-0.56	0.33	N/A
Fantozzi [79] (stair ascent)	-1.24	-2.2	-0.27	0.37	N/A
MB					
Overall	**-1.48**	**-2.09**	**-0.88**	N/A	**0.00%**
Sosio [77] (level walking)	-1.16	-2.23	-0.09	0.32	N/A
Catani [29] (stair ascent)	-1.52	-2.53	-0.51	0.36	N/A
Fantozzi [79] (stair ascent)	-1.76	-2.80	-0.71	0.33	N/A

Combined FB and MB groups ambulated with decreased maximum knee flexion in swing than controls across level walking and stair ascent (-1.41; UCI=-2; LCI=-0.81) (Table 10). No differences outside of the 95% confidence levels were found between FB and MB patients.

2.4 Discussion

Tibesku et al. [10] was the only study which utilised the same prosthesis implantation configuration, with the PCL retained in both the FB and MB groups. Fantozzi et al. [79] and Sosio et al. [77] sacrificed the PCL in the FB group, and retained the PCL in the MB group. Differences in PCL scenarios may be problematic when comparing prostheses, with Jacobs et al. [90] finding significant improvements in knee ROM to the order of eight degrees in patients who had the PCL sacrificed in comparison to patients with the PCL retained in a systematic review. The authors concluded, however, that the results should be interpreted with caution due to methodological variability.

Contrasting findings from the literature have suggested that TKR patients with the PCL retained ascend stairs with more normal quadriceps function than PCL sacrificed designs [84, 91, 92]. Other studies have found differences in kinetic variables, with Dorr et al. [93] finding greater medial compartment loading and higher knee joint reaction forces in PCL sacrificed designs, leading to the potential for reduced prosthesis durability. Misra et al. [94] discounted the role of the PCL in TKR surgery, finding no significant differences in cases where the PCL was retained or sacrificed, suggesting the PCL is not functional in most patients with a TKR. Other authors have detailed advantages of posterior stabilised designs over PCL retention with regards to a more stable component interface [95, 96] and increased ROM [95-98].

The evidence remains contrasting in the comparison of PCL sacrificed and retained total knee prostheses, although, despite the findings of Misra et al. [94], it appears an important consideration for comparative research. Such differences could attenuate the often small, but significant differences between prosthesis designs, potentially leading to the misinterpretation of results. It is important, therefore, that research comparing FB and MB prostheses utilise the same PCL configuration to enable valid comparisons.

Three of the five included studies stated the duration after surgery that the gait analyses were undertaken [29, 79, 80], displaying large differences between FB and MB groups. When comparing groups, it is accepted that confounding variables should be minimised where possible. Differences in the duration after surgery the gait analyses were undertaken to the order of magnitude observed in the three studies, questions whether the patient groups were well matched with regards to rehabilitation status. It has been argued, however, that most changes in physical function occur within six months following TKR surgery [99]. Kennedy et al. [100] also reported the greatest improvements during the first 12 weeks post-surgery and that slower improvements continued to occur from 12 to 26 weeks. De Groot et al. [101] further suggested that most rehabilitation programmes stop at nine months post-surgery, therefore questioning whether further improvements in function would occur after this. These data suggest that the effect of rehabilitation status is likely to be negated after six to nine months post-surgery.

In light of these findings, it is advised that future studies should describe the duration after surgery the gait analyses were undertaken, with the distribution about the mean appropriately explained in order to confidentially infer the results of the study. It is also advised that studies should control the duration after surgery that the gait analyses were undertaken where possible in order to reduce potential bias relating to rehabilitation status.

From the meta-analysis, it was identified that combined FB and MB groups ambulated with decreased gait velocity than controls during walking [77], stair ascent [29, 79], and stair descent [29]. This finding is consistent with McClelland et al. [9], who identified that eight of eleven patient groups walked slower than controls at self-selected gait velocity after TKR surgery in a systematic review [102-105]. Slower walking speeds have also been found in patients with knee OA when compared to controls [106-109]. The collated findings of this review suggest no differences in gait velocity between FB and MB prostheses, with no differences outside of the 95% confidence intervals.

It was also found that combined FB and MB groups ambulated with increased stance phase duration than controls during walking [77], stair ascent [29, 79], and stair descent [29]. No differences were found between FB and MB prostheses, with no differences outside of the 95% confidence intervals. A reduction in gait velocity and increased stance phase duration have been suggested to be associate factors of a ‘stiff knee’ gait pattern [104, 105, 110, 111], a feature that is consistent within different TKR designs [84, 91, 93]. Dorr et al. [93] associated this pattern with an increased flexion moment, and a greater requirement for quadriceps and biceps femoris activity. It has been postulated that these mechanisms are adopted to reduce shear forces [93], or attributed to patterns developed prior to TKR surgery [111, 112]. Consistent effect size magnitudes of >1 (Cohen’s *d*) were found which suggest a large overall effect [113, 114] between TKR and control groups in gait velocity and stance phase duration, indicating substantial differences between patients and controls in the commonly reported spatiotemporal variables. No differences, however, were identified between FB and MB prostheses.

From the kinematic cross study comparisons, combined FB and MB prostheses ambulated with reduced maximum knee flexion at initial contact than controls during stair ascent [29, 79], however, no differences were observed with the inclusion of walking [77]. No differences were found between FB and MB prostheses outside of the 95% confidence intervals. When the knee is in a more extended position at initial contact as observed in the collated findings during stair ascent, this suggests 'quadriceps avoidance gait', which is characterised by extension of the knee throughout the stance phase of gait [115]. Andriacchi et al. [116] attributed this pattern, which is similar to that observed in symptomatic anterior cruciate ligament (ACL) knees, to proprioceptive impairment and the disruption of the mechanical advantage mechanism during knee flexion. This subsequently leads to instability and weakness during functional activity [116]. In a review of gait analysis after TKR surgery, McClelland et al. [9] found that three out of 11 authors had reported knee flexion at initial contact. Chen et al. [105] found reduced knee flexion at initial contact in PCL retained and PCL sacrificed TKR groups, although no differences were found by Smith et al. [117] and Wilson et al. [91] between TKR groups and controls.

In the collated findings from the current study, both FB and MB groups ambulated with reduced maximum knee flexion than controls during level walking [77] and stair ascent [29, 79]. There were, however, no differences between FB and MB groups. Large overall effects of >1 were calculated between TKR and control groups in the commonly reported kinematic variables [113, 114]. Reduced maximum knee flexion during swing in post-surgery TKR patients is a common finding, with a number of authors detailing this [91, 102, 104, 105, 117]. This reduction has been shown to develop prior to TKR surgery in patients with OA [106], and be a predictor of surgical outcome following surgery at the pre-surgery time point [117]. It also contributes to achieving an adequate ROM at the knee which is an important determinant of functional activity following TKR surgery [118]. Despite these findings, no kinematic differences between FB and MB prostheses could be identified from the available literature. The small number of commonly reported variables may account for this, with only two of seventeen variables reported by the three studies that were included in the meta-analysis.

No common kinetic variables were observed within the three studies eligible for inclusion in the meta-analysis [29, 77, 79], highlighting the inconsistencies in methodological reporting. Sosio et al. [77] reported the maximum knee extension moment to be lower in the FB and MB groups ($p<0.002$ and $p<0.001$, respectively) when compared to controls during level walking. The authors did not state the values of the knee extension moments, but rather the sagittal plane knee angles at the point of the maximum knee extension moment. In the FB group, this was reached at 3.80±6.30° at 27.9 ±28.0% of the stance phase, and at 9.20±8.90° at 32.1 ±34.6% of the stance phase in the MB group. No statistical analysis was reported, although a moderate difference was apparent at the degree of knee flexion where the maximum knee extension moment occurred (5.40°). This may suggest that patients with a FB prosthesis in this instance limit quadriceps recruitment by keeping the knee more extended, signifying a potential quadriceps avoidance pattern that is often apparent in the ACL deficient knee [115, 119-121].

Kramers-de Quervain et al. [80] found few differences across the spectrum of variables, with only a discernible contrast in loading rate between FB and MB prostheses. The MB side displayed a higher mean loading rate (6.67kN/s) than the FB side (4.65kN/s), a difference of 2.26kN/s, however, the authors did not report whether this was significant. No consistency in kinetic reporting was evident between Kramers-de Quervain et al. [80] and Sosio et al. [77] investigating level walking.

Between FB and MB differences were reported in the maximum knee extension moment during stair ascent [79]. Fantozzi et al. [79] found the MB group ascended with a reduced ($p=0.02$) maximum knee extension moment when compared to the FB group. In addition, Catani et al. [29] also found that the sagittal knee moment during late stance phase showed an abnormal pattern in the MB group, with the FB group displaying a maximum knee flexion moment in one out of ten patients, and the MB group in seven out of ten patients during stair ascent. This pattern was also observed during stair descent [29], with the MB group showing a reduced maximum knee extension moment compared to the FB group. The authors suggested that the MB groups compensated for weak quadriceps during both stair ascent and descent, by moving the point of force application to the ground closer to the centre of rotation with a view to stabilising the joint.

The MB groups also displayed reduced maximum knee adduction moments when compared to the FB groups during stair ascent [29, 79]. A reduced maximum knee adduction moment indicates a decrease in medial compartmental loading, thus suggesting the adoption of compensatory mechanisms. Interestingly, the authors also reported an increase in the lateral trunk tilt towards the implanted knee in MB patients, which may suggest a mechanism to optimise the central location of the prosthesis. No differences, however, were found in the maximum knee adduction moment between FB and MB groups during stair descent [29].

2.4.1 Limitations

Full text articles not published in English were excluded, therefore, data of potential importance may have been overlooked. One such article was a study by Mockel et al. [78]. A translated abstract of the original German paper was available in English, with the authors finding a greater mean stance phase knee flexion in MB knees (14.1°) when compared to FBs (10.8°). This, coupled with the findings of Kramers-de Quervain et al. (1997), suggest MBs may increase ROM, a principle theoretical benefit of the MB design [14].

A limitation of published data, and thus systematic reviews, is that of the 'file drawer' effect. This relates to the suggestion that all published studies are a biased sample of the studies actually carried out [122], whereby typically, published articles are biased towards significant findings. Not all of the included studies showed significant differences between FB and MB groups, however, this is still of consideration when interpreting the literature, and may lead to over interpretation of the differences between FB and MB total knee prostheses. A further limitation is the assessment of study design through the medium of reporting quality, a recognised limitation of systematic reviews [123]. It is important to note that the failure of an article to report specific criteria is not conclusive proof that they were not met, although transparent reporting is important to enable analyses such as this to be undertaken.

Due to the lack of studies retrieved and subsequently included in the meta-analysis, the grouped findings are of questionable implication. This further highlights the requirement for additional work in this area in order to adequately determine whether MB implantation improves knee biomechanics during ADLs.

2.4 Conclusions

- There have been few studies that have compared FB and MB total knee prostheses during functional activity using gait analysis.
- The deficiency of the available research makes the clinical interpretation of the findings difficult, and highlights the requirement for further work.
- There was little substantial evidence available regarding kinematic differences between FB and MB prostheses during level walking, stair ascent, and stair descent. Evidence from Kramers-de Quervain et al. [80] and Mockel et al. [78] do suggest, however, that MB implantation may improve knee kinematics.
- Stair ascending gait in MB patients showed reduced knee extension moments in comparison to FB patients [79]. Further evident in MB patients was a reduction in knee adduction moments, suggesting reduced medial compartmental loading [29, 79]. The combination of a reduction in knee extension and adduction moments suggests lower limb compensatory mechanisms may be present in the MB knee, providing evidence of a protective knee pattern due to potential instability.

3.0 General methods

This thesis was based around two underpinning methods. The primary method was the use of three dimensional motion analysis integrated with force transducers to derive spatiotemporal and three dimensional kinematic and kinetic variables. This was a laboratory based system used in Chapters 4, 5, 6, and 7. The secondary method was the use of electrogoniometry, combined with accelerometry, in order to determine sagittal knee kinematics and physical activity during free living conditions away from the laboratory. This system was used within Chapters 7 and 8.

This chapter primarily details the administrative details, system instrumentation, system set-up, testing protocols, and data processing relating to the two methods. Other pertinent information, such as the total knee replacement (TKR) procedure, is also described in this chapter. Information that differs between some chapters, such as participant details and statistical analyses, are detailed within the individual chapters for clarity.

3.1 Ethical approval

Approvals for experimentation involving control participants were granted by the Faculty of Health and Life Sciences Ethics Committee at Northumbria University. Two reviewers independent of the research investigation reviewed the applications as chosen by the Chair of the Ethics Committee. These applications were coded 'SUB56'.

For experimentation involving NHS patients, approval was sought from the County Durham and Tees Valley Two NHS Regional Ethics Committee. The application was successfully defended at a meeting of the committee, with the study being awarded favourable ethical opinion. The study protocol was peer-reviewed and validated by process of committee review before the Research and Development Department of the Gateshead Health NHS Foundation Trust. This application was coded '10/H0908/13'.

3.2 Set-up of the three dimensional motion analysis system

A 12 camera three dimensional motion analysis system (Vicon MX, Oxford, UK) was calibrated through a standard dynamic protocol using a five marker calibration wand (Vicon, Oxford, UK) in Chapters 4, 5, 6, and 7. The 'aim camera' function in Nexus (version 1.7.1, Vicon, Oxford, UK), the instrumentation set-up and analysis software for the system, was used prior to calibration to determine the optimal camera placement and orientation for the movements undertaken. The calibration was accepted when all 12 cameras (Vicon T20, Oxford, UK) exhibited an image error of <0.2mm. The volume origin of the cameras was set with the calibration wand placed at a predetermined and consistent origin in the centre of the volume in order to determine the camera orientation for the session. Adjustable handrails were used along the length of the laboratory and instrumented stair rig for patient testing as a safety precaution. The handrails were removed in the testing of controls to reduce unnecessary marker occlusion. Kinematic data were captured at 200Hz into the Nexus software. Figure 4 depicts the laboratory set-up.

Figure 4 – Set up of the gait laboratory

Four force plates (OR6-7, AMTI, Watertown MA, USA) (width = 464mm; length = 508mm; depth = 82.6mm) were embedded within a 7m walkway in the centre of the calibrated volume. Each force plate was connected to a digital strain gauge amplifier

(MiniAmp MSA-6, AMTI, Watertown MA, USA), with each of the three dimensions of force and moment amplified by a gain of 1000.

A physiotherapy training staircase unit (Physio-Med Services LTD, Glossop, UK) that consisted of three steps (width=630mm; length=270mm; depth=200mm; pitch = 65°) was located at one end of the laboratory walkway. This was modified to accept a force plate (MC818, AMTI, Watertown, MA, USA) (width=558.8mm; length=203.2mm; depth=79.2mm), with the original first step removed. The stair rig conformed to the British Standards Institution guidelines (BS 5395-1:2000, sub section 3.1.1) for private stair cases.

The amplified signals from all five force plates were connected to one of the two Vicon MX Giganet core processing units (Vicon, Oxford, UK) via a patch box. The force plates had a stated linearity of ±0.2% and a stated hysteresis of ±0.2%. Kinetic data were captured at 1000Hz.

Participants had their height and mass taken, along with bilateral leg length, and knee and ankle widths, in order to fit the participant's specific dimensions to the lower body 'Plug in Gait' model (Vicon, Oxford, UK). The 'Plug in Gait' model is a derivative of the Helen Hayes model [124-126], and is used routinely in clinical gait analyses [127]. The measurements were undertaken in line with the recommendations of the 'Plug in Gait' model [128], and are detailed below:

- Height was measured with the participant standing upright with their head in the plane where the imaginary line joining the orbitale to the tragion is perpendicular to the long axis of the body. Measurement was undertaken barefoot using a telescopic measuring rod (SECA 224, Birmingham, UK) attached to a scale (SECA 701, Birmingham, UK).

- Mass was measured using a calibrated scale (SECA 701, Birmingham, UK).

- Leg length was determined between the anterior superior iliac spine and the medial malleolus, via the knee joint. The measurement was undertaken with the participant lying supine on an examination bed using a measuring tape (SECA 201, Birmingham, UK).

- Knee width was measured and defined as the medio-lateral width of the knee across the line of the knee axis. The measurement was performed in weight bearing with the participant standing in the anatomical position using manual callipers (Bicondylar Caliper, Holtain, Crymych, UK).

- Ankle width was measured and defined as the medio-lateral width across the malleoli. The measurement was performed in weight bearing with the participant standing in the anatomical position using manual callipers.

Participants were asked to flex and extend their knee whilst sitting on the edge of an examination bed to determine the specific location for the attachment of the lateral epicondyle knee markers required after static calibration. The skin surface on the lateral aspect of the knee joint was observed in order to identify an area of minimal skin displacement during flexion and extension.

Ten retroflective markers (Ø=14mm), and four stick markers (Ø=14mm) with a lateral protrusion of 85mm and 80mm for the thigh and shank, respectively, were placed bilaterally over anatomical landmarks on the lower body in line with the recommendations of the system manufacturer [128] for the lower body 'Plug in Gait' model. These positions are appended below:

- Two markers were placed directly over the anterior superior iliac spines (LASI and RASI).

- Two markers were placed directly over the posterior superior iliac spines. These were located inferior to the sacro-iliac joints (LPSI and RPSI).

- The first left stick marker was placed on the distal lateral third of the left thigh just below the swing of the hand, in line with the hip and knee joint centres

(LTHI). The first right stick marker was placed on the proximal lateral third of the right thigh in line with the hip and knee joint centres (RTHI).

- The second left stick marker was placed over the distal lateral third of the left shank (LTIB). The second right stick marker was placed over the proximal lateral third of the right shank (RTIB). The tibial markers lay on the plane that contained the knee and ankle joint centres and the ankle flexion/extension axis. The placement of the markers reflected the external rotation of the shanks with respect to the knee flexion axes during standing in the anatomical position.

- Two markers were placed over the lateral malleoli along an imaginary line that passes through the transmalleolar axis (LANK and RANK).

- Two markers were placed over the heel on the calcaneus at the same height above the plantar surface of the foot as the toe marker (LHEE and RHEE).

- Two markers were placed over the second metatarsal heads, on the mid-foot side of the equinus break between the fore-foot and mid-foot (LTOE and RTOE).

Two knee alignment devices (KADs) (Vicon, Oxford, UK) were placed bilaterally over the medial and lateral epicondyles whilst the participants were standing in the middle of the three dimensional calibrated volume. The KADs, consisting of the markers KAX, KD1, and KD2, were used to independently define the alignment of the knee flexion/extension axis when the participant was standing in full extension. The distance between each of the markers was a constant 144mm which enables the software to establish a virtual knee marker at the central joint of the KAD, such that the directions from the point are mutually perpendicular. The point which gives the line between KAX and KNE closest to parallel to the lateral direction of the pelvis is taken as being the correct solution, thus allowing measurement of the anatomical flexion axis. The Nexus software subsequently calculates the relative transverse alignment of the axis, to the transverse plane orientation of the thigh and shank, as calculated using the asymmetric thigh and shank stick markers. These relative alignments were then applied to all proceeding dynamic trials in each participant.

Following data capture of a static trial, the KADs were removed and two retroflective markers (Ø=14mm) were placed bilaterally over the lateral femoral epicondyles of the knee (LKNE and RKNE). Figure 5 depicts the anatomical positioning of the markers.

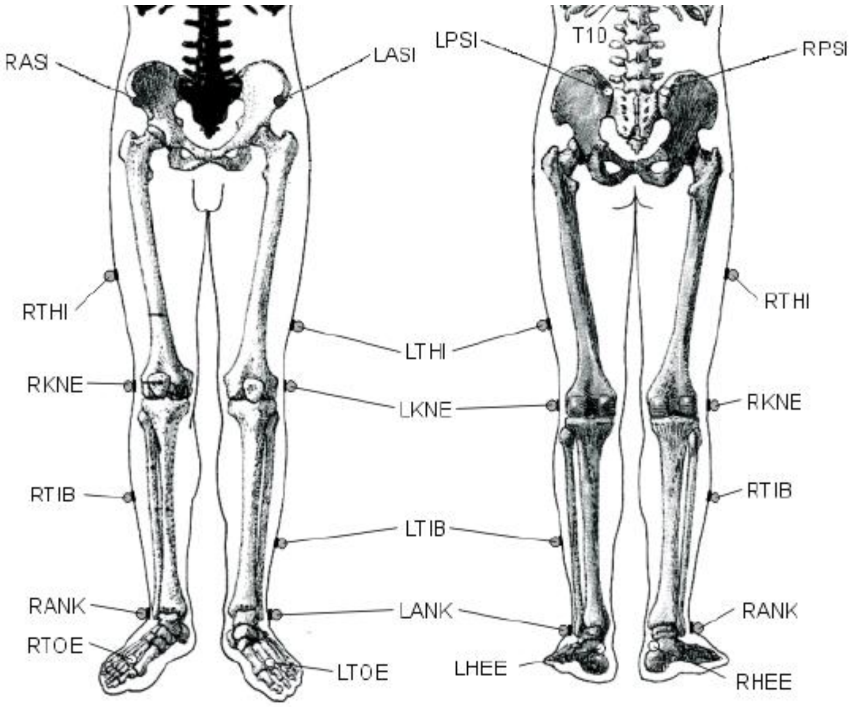

Figure 5 – Anatomical position of the markers used in the lower body 'Plug in Gait' model [129]

3.2.1 Activities of daily living protocol used in the three dimensional motion analysis system

Participants included in Chapters 4, 5, and 7 undertook a number of walking trials along the 7m laboratory walkway until three bilateral initial contact and toe off events were collected on a force plate. In Chapters 4, 6, and 7 (Experiments 1 and 3), three bilateral stair ascent trials were then performed on the instrumented stair rig. Participants were instructed to ascend in an alternate 'step over step' manner whereby one foot was placed on each step, with the first step being the force plate. From standing at the top of the stair rig, participants then undertook three bilateral stair descent trials using the same alternate 'step over step' procedure. Trials were excluded from the analysis if the participants used the handrails. Participants included in Chapter 7 undertook the same protocol; however, data were collected on the right side only. Figure 6 depicts the instrumented stair rig used in the experimentation.

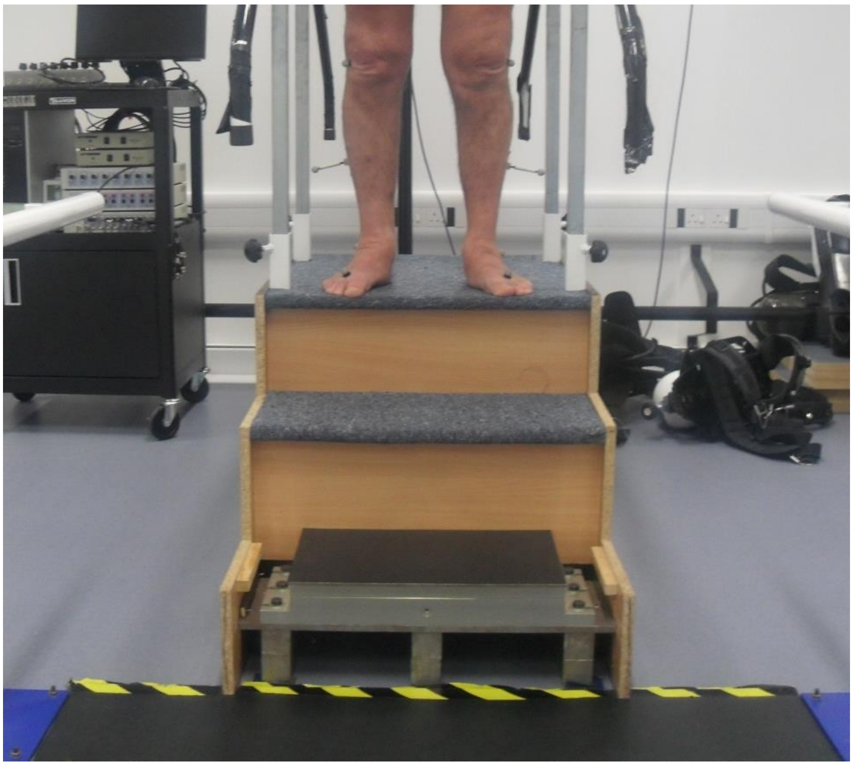

Figure 6 – The instrumented stair rig used for stair ascent and stair descent trials in Chapters 4, 6, and 7

Three sit to stand trials from an orthopaedic stool (Nottingham Rehab Supplies, Nottingham, UK) (length=320mm; width=260mm) were performed in Chapters 4, 6, and 7. The height of the orthopaedic stool (Figure 7) was normalised in Chapters 4 and 6, with participants starting the movement with their knees flexed to 90°. This was measured using a manual goniometer (Protractor goniometer, Prestige Medical, Blackburn, UK). Normalisation of the starting position was undertaken to enable comparison of patients with differing anthropometric characteristics when comparing fixed bearing (FB) and mobile bearing (MB) prosthesis groups. In Chapter 7, the stool was kept at the standard height of 560mm as normalisation was not required in the validation of the electrogoniometer.

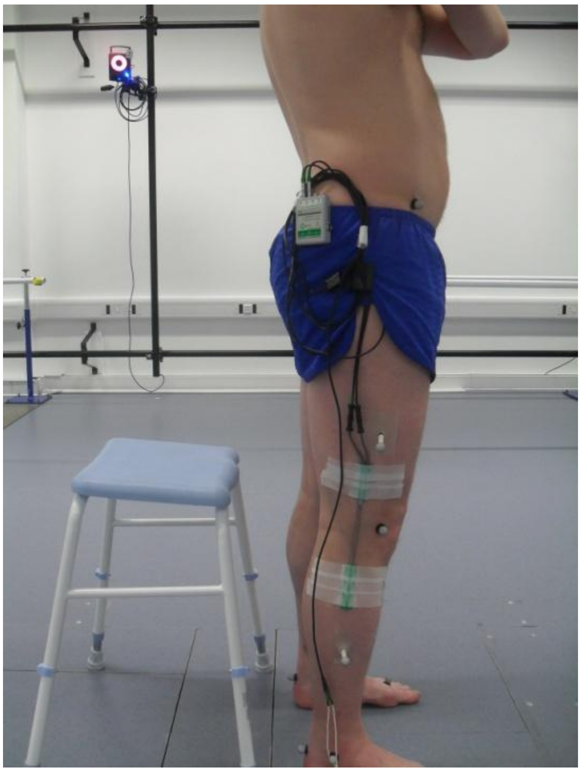

Figure 7 – The orthopaedic stool used for the sit to stand and stand to sit trials

During the sit to stand movement, participants were instructed to cross their arms and displace them superiorly so that the upper arm was parallel to the floor in the sagittal plane to prevent marker occlusion. Three stand to sit trials were then performed, with the participants adopting the modified arm position. The orthopaedic stool was maintained at a consistent height to the sit to stand trials during stand to sit. Walking, stair ascent, stair descent, sit to stand, and stand to sit movements were all performed at a self-selected velocity and undertaken barefoot. Patients in Chapters 4, 5, and 6 were tested prior to surgery, three months post-surgery, and nine months post-surgery.

3.2.2 Data cleaning and processing in the three dimensional motion analysis system

Initial contact and toe off events in walking, stair ascent, and stair descent were determined by the visual onset and disappearance of the ground reaction force (GRF) vector in Nexus, respectively. Trials were only included, therefore, when initial contact (0% of the gait cycle) and toe offs occurred on a force plate. The threshold for the visual onset of the GRF vector in Nexus was set at 20N, a default magnitude recommended by the manufacturer for use with gait analyses. This means, therefore, that the first frame at which the GRF was >20N was taken as the event of initial contact. The subsequent frame at which the GRF was <20N was taken as the event of toe off. Due to having only one force plate in the stair rig, the second initial contact in stair ascent and stair descent (100% of the gait cycle) was determined by the visual identification of post-filtered marker trajectories (z axis) from graphical outputs in conjunction with the reconstructed figure in Nexus.

In the sit to stand trials, the point at which the ASIS markers began to displace with a superior displacement (z axis) was defined as the start point, with the end point defined as when the superior displacement curve levelled. This was undertaken by visual identification of the post-filtered trajectories from graphical outputs, in addition to the reconstructed figure in Nexus. Optimisation of this accuracy during sitting and standing trials was not required as the area of interest was away from the trial extremities. This was supported in the post-hoc analysis, as the area of interest relating to the maximum loading ratio and angular velocity, occurred between a range of 10%-20% of the movement cycle.

Raw data for all activities were processed in Nexus by filling marker trajectory gaps using a Woltring quintic spline routine when the gaps were <10 frames [130]. Longer gaps were filled using a pattern fill function, adopting the trajectory of a marker with a similar displacement trail. Marker trajectories and kinetic data were filtered using a fourth order Butterworth filter with zero lag. An upper cut off frequency of 6Hz and 300Hz was used for marker trajectories and kinetic data, respectively. The dynamic gait model was subsequently applied, implementing a lower body inverse dynamic analysis to resolve the three dimensional joint moments.

In Chapters 4, 5, and 6, walking, stair ascent, and stair descent trials were imported into Polygon Authoring Tool (version 3.5.1, Vicon, Oxford, UK) to normalise the trials to gait cycle percentage. Moments were normalised to Newton metres per kilogram of body mass (Nm/kg). Across all activities in Chapter 7, and the sit to stand and stand to sit trials in Chapters 4 and 6, the post-filtered comma separated files were accessed to derive the post-filtered sagittal knee angular displacements.

In Chapters 4, 5, and 6, the spatiotemporal variables analysed were cadence, foot off percentage, stride length, stride time, and gait velocity for walking, stair ascent, and stair descent.

The knee kinematic variables analysed were minimum knee flexion angle, maximum knee flexion angle, sagittal knee range of movement (ROM), maximum knee abduction, maximum knee adduction, frontal knee ROM, maximum knee external rotation, maximum knee internal rotation, and axial knee ROM during walking, stair ascent, and stair descent.

The knee kinetic variables analysed were maximum knee extension moment, maximum knee flexion moment, knee flexion at maximum knee extension moment, knee flexion at maximum knee flexion moment, maximum knee abduction moment, maximum knee adduction moment, maximum knee external rotation moment, and maximum knee internal rotation moment during walking, stair ascent, and stair descent.

Specific point variables encompassing the maximum, minimum, and range from the continuous waveforms were used in the statistical analyses as they have a greater potential to characterize knee gait patterns [131]. Continuous waveforms depicting sagittal knee kinematics were also used in Chapters 5 and 6 in order to further analyse the hypothetical kinematic advantages of MB implantation [78, 80, 132]. Maximum knee extension velocity and loading ratio were analysed for sit to stand, with maximum knee flexion velocity and loading ratio analysed for stand to sit.

3.3 Electrogoniometry and accelerometry systems

A twin axis electrogoniometer (SG150, Biometrics, Gwent, UK) was used in Chapters 7 and 8 as a method of measuring sagittal knee kinematics away from the laboratory (Figure 8). The electrogoniometer was 274mm in length, excluding the cable attachment housing, with the proximal (width=18mm; length=54mm; depth=5mm) and distal (width=18mm; length=70mm; depth=5mm) endplates asymmetric in dimension. The electrogoniometer contained a composite cylinder inside a flexible shim in which a series of strain gauges were mounted between the two endplates. As the angle between the endplates changed, the strain induced an electrical resistive charge which was measured through a voltage proportional to the angle. The components were mounted inside a tightly coiled and lightweight spring to prevent damage to the device and injury to the participant. The proximal endplate contained electrical connections for the cable attachments to the preamplifier.

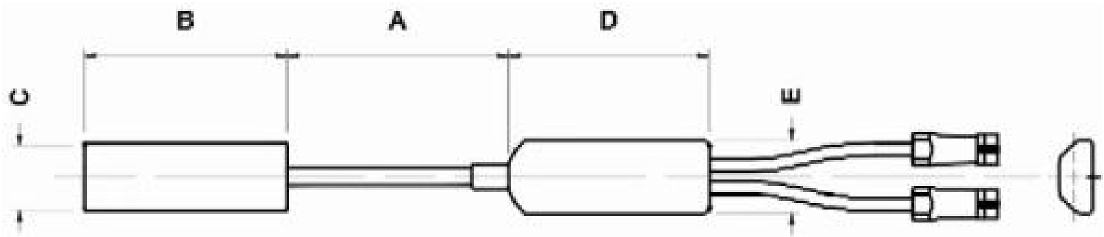

Figure 8 – Biometrics SG150 electrogoniometer (not to scale). A = 150mm; B = 70mm; C = 18mm; D = 54mm; E = 20mm [133]

The electrogoniometer was attached to a small, portable, battery powered data logger with eight channels (Data logger, MIE Medical Research, Leeds, UK) via a preamplifier (Preamplifier, MIE Medical Research, Leeds, UK). The preamplifier had a mass of 10g, excluding the cable and connector, and a frequency response of 6Hz to 6000Hz at 3dB. A pre-amplification gain of 1000 was used in all studies. The data logger (width=55mm; length=72mm; depth=18mm) had 8 programmable channels, a programmable sampling rate of 10Hz to 4000Hz, a mass of 90g including the memory card (512MB), and was powered by one 1.50V AA battery. A Procell MN1500 battery (1.5V Alkaline Manganese Dioxide 2700mAh, Duracell, UK), recommended by the manufacturer for use with electrogoniometers, was used in the investigations. A sampling frequency of 200Hz was selected for consistency with the motion analysis system during Chapter 6, as well as previous research using electrogoniometry [134-136].

To allow synchronisation with the three dimensional motion analysis system, two electronic foot switches (Foot switch, MIE Medical Research, Leeds, UK) were used in Chapter 7 Experiment 1. The foot switches were utilised for walking, stair ascent, and stair descent trials in which initial contact and toe off events occurred. Sit to stand and stand to sit trials began with the participant balancing on the contralateral leg with the ipsilateral leg held above the force plate, and then placing the ipsilateral leg in contact with the force plate to enable accurate synchronisation between systems prior to undertaking the activity. The foot switches were also used in Chapter 7 Experiment 3 for movement cycle identification purposes.

The electronic foot switches were attached with the participants lying prone on an examination bed. Double sided hypoallergenic tape (Natural Image, London, UK) (width=25mm) was used to attach one foot switch to the forefoot, posterior to the inferior surface of the toes. The second foot switch was attached to the inferior surface of the heel, aligning the posterior surface of the foot switch to the posterior aspect of the heel. Finepore microporous tape (Premier, Brighton, UK) (width=25mm) was used to secure the attachment of the foot switches. A foot switch encoder (Foot switch encoder, MIE Medical Research, Leeds, UK) connected the two foot switches to the second channel of the data logger.

During electrogoniometer attachment in Chapters 7 and 8, the participants were asked to stand upright in the anatomical position, with the knees in full extension. Pilot experimentation revealed that the electrogoniometer could be placed on the anatomical line from the greater trochanter of the femur, through the lateral epicondyle, to the lateral malleolus. It was found that the knee marker placed on the lateral epicondyle, required for dynamic trials in motion analysis, did not obstruct the flexible shim of the electrogoniometer during knee flexion. This was investigated due to the previously suggested problems reported by Pomeroy et al. [137] for validation in Chapter 7 Experiment 1.

The anatomical line was marked between the greater trochanter of the femur and the lateral epicondyle in the sagittal plane. The same protocol was undertaken for the shank, with the line between the lateral epicondyle and the lateral malleolus identified and marked (Figure 9). Double sided hypoallergenic toupée tape was used to attach the endplates to the skin. Multiple strips of Finepore microporous surgical tape were applied perpendicular to the endplates to secure attachment. The participants were then asked to flex and extend their knee throughout their full ROM to ensure the attachment was secure and to visually identify areas of movement between the skin and electrogoniometer.

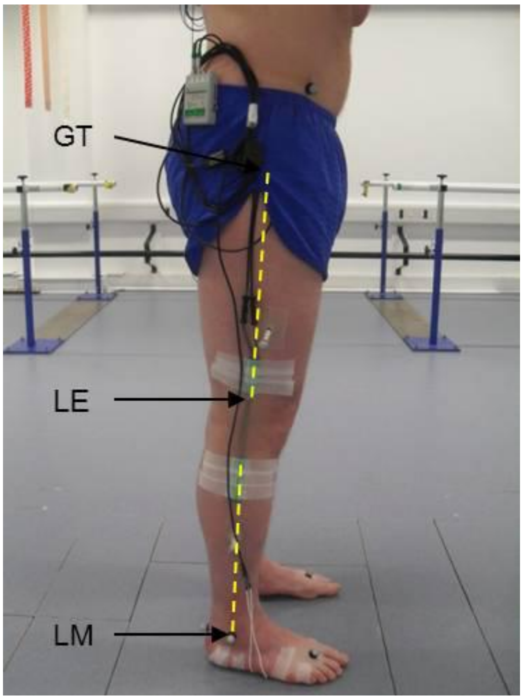

Figure 9 – Set-up of the electrogoniometry system for validation in Chapter 7. GT = greater trochanter; LE = lateral epicondyle; LM = lateral malleolus

The preamplifier and accompanying cables were attached to the electrogoniometer and data logger. The cables were coiled together and secured using Finepore microporous surgical tape to prevent instrument displacement. The data logger was then clipped onto the top of the participant’s shorts, or placed into a pocket of the shorts, depending on the preference of the participant and where the device was least likely to impede movement.

In Chapter 7 during laboratory attachment, the data logger was connected to the laboratory computer prior to testing. The ‘live preview’ function in MyoDat (version 6.59.0.8260, MIE Medical Research, Leeds, UK), the instrumentation set-up and analysis software for the data logger, was used to observe the real time output of the electrogoniometer and foot switches. The participants were asked to flex and extend their knee throughout their full ROM, as well as placing their ipsilateral forefoot and heel in contact with the ground to verify correct operating function of both instruments. This process was not undertaken in Chapter 8 when the system was attached at the patient’s home and foot switches were not used.

In Chapter 7 Experiment 2 and Chapter 8, a calibrated accelerometer (GT3X, Actigraph, Pensacola, FL, USA) (length=53mm; width=50mm; depth=20mm) with a mass of 42.5g was worn on an elastic belt at the midaxillary line of the right hip, a position suited to picking up normal ambulatory movement [138]. Prior to attachment, the device was connected to a computer and set-up using ActiLife (version 5, ActiGraph, Pensacola FL, USA). Accelerations in three axes (infero-superior, antero-posterior, and medio-lateral) were selected [139], and were converted into 'count' values, which increase in a linear function with the magnitude of accelerations [140]. Post-filtered and accumulated data were stored in user-specified time intervals, referred to as 'epochs'. The lowest programmable epoch compatible with the GT3X device was one second, which was chosen for use in this experiment. For each epoch interval, data samples taken from the accelerometer inside the device at a rate of 30Hz were first filtered and then accumulated before being stored in memory. As the device was programmed to collect one second epoch data, 30 accumulated samples were stored for each enabled axis on the device every second [141].

The raw acceleration signal was passed through an analog band-pass filter, the output of which yields a dynamic range of 4.26 ±2.13g/s at 0.75Hz (centre frequency of the filter). The filtered signal was then digitised into 256 distinct levels by an 8-bit solid-state analog-to-digital converter, producing 4.26g/sec per 256 levels or 0.01664g/sec/count. When each filtered sample was multiplied by the sample window of 0.1s, a resolution of 0.001664g/count was achieved [142]. The same ActiGraph accelerometer and firmware was used in all testing (version 1.3.0). This was imposed to prevent potential differences between firmware versions [139].

3.3.1 Ambulatory protocol used in the electrogoniometry and accelerometry systems for testing away from the laboratory

In Chapter 7 Experiments 1 and 3, the protocol used for the electrogoniometry system was the same as that described in Section 3.2.1. This section, therefore, relates specifically to testing away from the laboratory presented, in part, for the analysis of reliability in Chapter 7 Experiment 2, and exclusively in Chapter 8 for the comparison of FB and MB groups.

In Chapter 7, participants were asked to arrive at the laboratory by 7.40am on the day of testing, with measurement beginning at a standardised time of 8.00am. Following electrogoniometer and accelerometer attachment, the data logger was clipped onto the top of the participant's shorts, or placed into a pocket of the shorts, depending on the preference of the participant and where the device was least likely to impede ambulation. Participants then put on a pair of trousers over the top of the shorts and attached instrumentation. It was suggested to the participants prior to testing to wear loose fitting trousers, or equivalent, to prevent constraint of the electrogoniometer and accompanying instrumentation during everyday physical activity. In Chapter 8, patients were visited at their home at 7.40am, rather than travelling to the laboratory.

The data logger was activated at 8.00am and the participants were requested to go about their normal everyday physical activity, apart from those concerning significant bodily contact with water. Participants in Chapter 7 were then asked to return to the laboratory, with patients in Chapter 8 visited at home in order to remove the instrumentation at 4.00pm.

3.3.2 Data cleaning and processing in the electrogoniometry and accelerometry systems

In Chapter 7 Experiments 1 and 3, trials were uploaded into MyoDat and exported as comma separated value files. These data were imported into Microsoft Excel (Microsoft, Redmond, WA, USA), and the trials were identified from the corresponding synchronous foot switch output. The trials were then imported into MATLAB (R2007b, Natick, MA, USA) and filtered using a low pass finite impulse response filter to determine the moving average of the signal. The filtered knee angle data in MATLAB across all activities were then differentiated to derive the angular velocity in Chapter 7 Experiment 1. The angular velocities of walking, stair ascent, stair descent, sit to stand, and stand to sit activities were derived to inform the upper velocity limit that the assessment of validity could be considered valid.

For testing away from the laboratory in Chapter 7 Experiment 2 and exclusively in Chapter 8, trials were uploaded into MyoDat and exported as text files. The trials were then imported into MATLAB, with the angular displacement data filtered using a low pass finite impulse response filter to determine the moving average of the signal.

To evaluate the sagittal knee angular displacement spectrum over the eight hour measurement period, the post-filtered angular displacement data were then manipulated in MATLAB to determine the magnitude of values falling within the incremental categories, or ‘bins’, defined in Table 11. MATLAB code that was used to undertake the calculations is detailed in Appendix H.

Table 11 – The 13 incremental categories used to analyse the spectrum of the angular displacement data across an eight hour ambulatory measurement period in ten asymptomatic participants

Angular displacement incremental categories		
$-10° \leq \theta < 0°$	$40° \leq \theta < 50°$	$90° \leq \theta < 100°$
$0° \leq \theta < 10°$	$50° \leq \theta < 60°$	$100° \leq \theta < 110°$
$10° \leq \theta < 20°$	$60° \leq \theta < 70°$	$110° \leq \theta < 120°$
$20° \leq \theta < 30°$	$70° \leq \theta < 80°$	
$30° \leq \theta < 40°$	$80° \leq \theta < 90°$	

‘θ’ equates to ‘Angular displacement’

There are a number of methods in the literature that quantify the number and range of categories for spectrum analyses. These include Sturges formula [143] which implicitly bases category size on the range of the data. There are also formulas developed by Scott [144] and Freedman-Diaconis [145] based on the standard error of measurement (SEM) and the interquartile range, respectively. These methods were not applicable in this instance as different populations over multiple trials were tested. Standardisation was required to prevent fluctuations in category sizes that would be dependent upon the distribution of data within a trial. Based upon previous research depicting sagittal knee angular displacements in 10° increments [146, 147], this magnitude was chosen for consistency.

Following the retrieval of the magnitude of raw values falling within the predefined incremental categories, the data were percentage normalised to time. The filtered knee angular displacement arrays were differentiated to derive the angular velocity (Appendix H). To evaluate the sagittal knee angular velocity spectrum over the eight hour measurement period, the post-filtered and differentiated angular displacement data were then manipulated in MATLAB to determine the amount of values falling between the angular velocity categories outlined in Table 12.

Table 12 – The 27 categories used to analyse the spectrum of the angular velocity data across an eight hour ambulatory measurement period in ten asymptomatic participants

Angular velocity incremental categories				
Zero	Flexion		Extension	
0 °/s	0°/s ≥ ω < -25°/s	-400°/s ≥ ω > -500°/s	0°/s ≤ ω < 25°/s	400°/s ≤ ω < 500°/s
	-25°/s ≥ ω > -50°/s	-500°/s ≥ ω > -600°/s	25°/s ≤ ω < 50°/s	500°/s ≤ ω < 600°/s
	-50°/s ≥ ω > -75°/s	-600°/s ≥ ω > -700°/s	50°/s ≤ ω < 75°/s	600°/s ≤ ω < 700°/s
	-75°/s ≥ ω > -100°/s	-700°/s ≥ ω > -800°/s	75°/s ≤ ω < 100°/s	700°/s ≤ ω < 800°/s
	-100°/s ≥ ω > -200°/s	-800°/s ≥ ω > -900°/s	100°/s ≤ ω < 200°/s	800°/s ≤ ω < 900°/s
	-200°/s ≥ ω > -300°/s	-900°/s ≥ ω > -1000°/s	200°/s ≤ ω < 300°/s	900°/s ≤ ω < 1000°/s
	-300°/s ≥ ω > -400°/s		300°/s ≤ ω < 400°/s	

'ω' equates to 'Angular velocity'

No authors have appeared to analyse the spectrum of angular velocity at the knee, therefore, no standardised protocol exists. Post-hoc analysis of the data found a large magnitude of values falling between 0°/s-100°/s. Four 25°/s incremental categories were subsequently used from 0°/s-(-/+100º/s) to further observe differences between categories with greater sensitivity in both flexion and extension. An additional category of 0°/s was also used to determine a fixed joint position. This does not relate to a true '0', but rather values less than the default 3 decimal digits of precision that was used, for instance <0.0005. Further post-hoc analysis supported the use of 100°/s incremental categories thereafter due to the lower percentage of knee angular displacement velocities above 100º/s.

Negative and positive angular velocities specific to flexion and extension, respectively, were then grouped to give the percentage of time spent at, or between, the magnitudes of velocity displayed in Table 13. This was undertaken due to there being negligible differences between flexion and extension categories in both Chapters 7 and 8. No differences were observed outside of one standard deviation (SD). These data were presented, and published out of, the 2nd International Conference on Ambulatory Monitoring of Physical Activity and Movement, Glasgow, UK (Appendix G).

Table 13 – The 13 incremental categories used to analyse the spectrum of the angular velocity data across an eight hour ambulatory measurement period in ten asymptomatic participants

Angular velocity incremental categories		
0°/s	100°/s ≤ ω < 200°/s	600°/s ≤ ω < 700°/s
0°/s ≤ ω < 25°/s	200°/s ≤ ω < 300°/s	700°/s ≤ ω < 800°/s
25°/s ≤ ω < 50°/s	300°/s ≤ ω < 400°/s	800°/s ≤ ω < 900°/s
50°/s ≤ ω < 75°/s	400°/s ≤ ω < 500°/s	900°/s ≤ ω < 1000°/s
75°/s < ω < 100°/s	500°/s ≤ ω < 600°/s	

'ω' equates to 'Angular velocity'

Accelerometry data were downloaded into ActiLife (version 5.0, Pensacola, FL, USA), the instrumentation set-up and analysis software of the accelerometer. Post-filtered acceleration threshold count values (0.001664g/count) recorded as the sum of the 30 accumulated samples every second were accessed. This gave the following values, 0 count = <0.001664g, 1 count = 0.001664g, 2 counts = 0.003328, 3 counts = 0.004992 and etcetera. Within the software, the acceleration magnitudes were combined at every data point to obtain the magnitude of the acceleration vector using Equation 1, thus giving an overall indicator of physical activity. The data were then transferred to MATLAB and subsequently converted from count values to acceleration in meters per second per second (Equation 2).

Equation 1 – ActiLife software processing to derive the acceleration vector

$$\text{acceleration vector} = \sqrt{x^2 + y^2 + z^2}$$

- 'x' = x axis of acceleration
- 'y' = y axis of acceleration
- 'z' = z axis of acceleration

Equation 2 – Transformation of count values to acceleration in MATLAB

$$\text{transformed} = \text{av} * 0.001664 * 9.80665$$

- 'av' = array containing the post-filtered acceleration vector 'counts'
- '0.001664' = magnitude of gravitational acceleration per count (g)
- '9.80665' = magnitude of gravitational acceleration in m/s^2

To examine the spectrum of gross acceleration over the eight hour measurement period, the post-filtered data were further processed in MATLAB for the magnitude of values falling at, or between, the incremental categories displayed in Table 14 (Appendix H).

Table 14 – The 13 categories used to analyse the spectrum of the gross acceleration data across an eight hour ambulatory measurement period in ten asymptomatic participants

Gross acceleration incremental categories		
$0m/s^2$	$1m/s^2 \leq a < 1.25m/s^2$	$2.25m/s^2 \leq a < 2.5m/s^2$
$0m/s^2 \leq a < 0.25m/s^2$	$1.25m/s^2 \leq a < 1.5m/s^2$	$2.5m/s^2 \leq a < 2.75m/s^2$
$0.25m/s^2 \leq a < 0.5m/s^2$	$1.5m/s^2 \leq a < 1.75m/s^2$	$2.75m/s^2 \leq a < 3m/s^2$
$0.5m/s^2 \leq a < 0.75m/s^2$	$1.75m/s^2 \leq a < 2m/s^2$	
$0.75m/s^2 \leq a< 1m/s^2$	$2m/s^2 \leq a < 2.25m/s^2$	

'a' equates to 'acceleration'

No authors have appeared to analyse the spectrum of physical activity using gross acceleration, therefore, no standardised protocol exists. Post-hoc analysis of the data suggested a large percentage of time at $0m/s^2$, and therefore a category of $0m/s^2$ was used to determine a period of no physical activity. Incremental categories of $0.25m/s^2$ were used thereafter due to the lower percentage of gross acceleration above $0m/s^2$. The total number of steps undertaken over the eight hour measurement period were retrieved from the summary spreadsheet as a further determinant of physical activity [148, 149].

3.4 Total knee replacement procedure

Following giving their written informed consent at the pre-surgery testing, the patient subset examined in Chapters 4, 5, 6, and 8 were randomised as to whether they would receive a fixed bearing (FB) (Sigma® Fixed Bearing Knee System, De Puy International, Leeds, UK) or mobile bearing (MB) (Sigma® Rotating Platform Knee System, De Puy International, Leeds, UK) total knee prosthesis. To ensure equal numbers in groups, randomisation was undertaken in blocks of four using a random number generator. For ethical reasons, patients were not blinded as to what prosthesis they received, and may have been told by the orthopaedic team whether they had a FB or MB prosthesis. The surgeon was notified on the day of surgery as to what implant the patient was receiving. Both FB and MB prostheses were posterior cruciate ligament (PCL) sacrificed, posterior stabilised, and had the patella resurfaced in all cases that required. One senior consultant orthopaedic surgeon performed all of the procedures.

Following surgery, patients undertook a post-surgery rehabilitation protocol in line with the procedures of the North East NHS Surgery Centre at the Queen Elizabeth Hospital (Gateshead Health NHS Foundation Trust). The initial post-surgery rehabilitation process is summarised in Table 15. This protocol was standard care at the time of testing.

Table 15 – The standard post-surgery rehabilitation procedures undertaken by total knee replacement patients at the North East Surgery Centre, Queen Elizabeth Hospital, Gateshead Health NHS Foundation Trust at the time of the testing

Day following TKR surgery	Physiotherapist rehabilitation procedures
Day 1	▪ Patients are full weight bearing with a walking aid ▪ Patients are shown bed transfer using a walking frame ▪ Whilst lying or sitting in a chair, patients undertake active assisted knee flexion, a static quadriceps stretch, a knee extension stretch, and a single leg raise. If the patients are unable to do a single leg raise, a mid range quadriceps contraction is undertaken ▪ Patients are advised to mobilise little and often throughout the day if they feel well enough and safe to do so. Most patients need a walking frame on the first day but some are well enough to progress to elbow crutches ▪ Patients are encouraged to use a cyrocuff to reduce swelling and inflammation, and are shown how to do so
Day 2	▪ The patient's mobility is assessed and they are progressed onto a pair of elbow crutches if possible ▪ Stair practice is undertaken (ascent and descent) if the patient's mobility is good enough ▪ Patients continue with exercises prescribed on day 1 and are progressed to more difficult movements if it is deemed possible
Day 3+	▪ Continuation of progression in the prescribed mobility exercises is undertaken ▪ Stair practice is further undertaken ▪ The patients are referred to the physiotherapy TKR group ▪ Patients are reviewed in a clinic by the consultant orthopaedic surgeon

4.0 Reliability of biomechanical variables in fixed bearing and mobile bearing total knee replacement patients and controls during activities of daily living

4.1 Introduction

Prior to evaluating the biomechanics of mobile bearing (MB) total knee prostheses compared to fixed bearing (FB) designs, it was important to establish the natural variability of gait variables in order to determine if a change in a gait variable was attributable to a real change or measurement error [150]. This is often referred to as the within-session reliability, and knowledge of this was important in determining the level of detectable change in the subsequent comparative work presented in Chapters 5 and 6 [151]. Further, due to potential variability in marker placement between gait analyses [126], it was important to determine the between-session reliability of kinematic data to aid the interpretation of both between-group and within-group analyses of FB and MB groups in Chapter 5 and 6.

This chapter details the within-session reliability for all spatiotemporal, knee kinematic, knee kinetic, maximum knee angular velocity, and loading ratio variables in FB, MB, and controls, in addition to the calculation of the minimum detectable change (MDC) for each individual variable. In addition, the between-session reliability and MDC were determined for all knee kinematic variables.

4.2 Method

4.2.1 Participants

4.2.1.1. Within-session reliability study

Nineteen patients with late stage primary knee osteoarthritis (OA) listed for total knee replacement (TKR) surgery were recruited from the Queen Elizabeth Hospital in Gateshead and randomised to receive a FB or MB total knee prosthesis as detailed in Chapter 3 (‘3.4 Total knee replacement procedure’). Three of the nineteen patients were excluded from the study after the pre-surgery gait analysis, with two patients allergic to a compound within the prosthesis. One patient had their surgery cancelled four times, amounting to 172 days between the pre-surgery gait analysis and surgery. It was proposed to exclude the patient from further analysis. No patients were lost to follow-up, and sixteen patients remained for analysis. Only seven patients were included in the FB group at nine months post-surgery due to one patient's follow-up period falling outside of the time period required for the initial completion of the degree programme.

Eight patients, five male and three female, received a FB prosthesis and had a mean age of 59.3 ±8.80yrs, height of 1.66 ±0.09m, mass of 87.9 ±16.1kg, and body mass index (BMI) of 31.9 ±4.86kg/m^2. Eight patients, five male and three female, received a MB prosthesis and had a mean age of 59.6 ±7.70yrs, height of 1.70 ±0.09m, mass of 91.2 ±12.4kg, and body mass index (BMI) of 31.9 ±6.80kg/m^2.

Inclusion criteria were patients listed for primary unilateral TKR surgery with OA who were aged between 45 to 80 years of age. Patients were excluded if they had previous knee or hip replacement surgery, had a pre-surgical valgus/varus deformity of ≥20° at the knee, suffered an infection of the knee joint post-surgery, or had any other significant unrelated lower limb injury or chronic condition that was deemed to have the potential to affect ambulation in the opinion of the Chief Investigator (Professor Deiary F. Kader).

Eight age and gender matched control participants were recruited from advertisements and informal contacts, forming part of a larger database of control data to be used by researchers at Northumbria University. Five male and three female participants had a mean age of 60.5 ±7yrs, height of 1.67 ±0.12m, mass of 72.58 ±9.43kg, and BMI of 26.06 ±1.21kg/m^2. The inclusion criteria were participants to be aged between 18 to 75 years of age and positive responses to the screening questionnaire (Appendix I). The exclusion criteria were no previous knee or hip replacement, no current lower limb injury, no previous conditions, operations, or other condition which could have had the potential to affect ambulation. Participant details are summarised in Table 16.

Table 16 – Fixed bearing (FB), mobile bearing (MB), and control group participant demographic and anthropometric details

	FB		MB		Control	
	Mean	SD	Mean	SD	Mean	SD
n	8	-	8	-	8	-
Male	5	-	5	-	5	-
Female	3	-	3	-	3	-
Age (yrs)	59.3	8.80	59.6	7.70	60.5	7.00
Height (m)	1.66	0.09	1.70	0.09	1.67	0.12
Mass (kg)	87.9	16.1	91.2	12.4	72.6	9.43
BMI (kg/m^2)	31.9	6.80	31.9	6.80	26.1	1.21

'SD' equates to 'Standard deviation'

Gait analyses were undertaken in the FB and MB groups at pre-surgery, three months post-surgery, and nine months post-surgery. One patient in the FB group acquired an unrelated lower limb injury at nine months post-surgery. The gait analysis was not undertaken until they were assessed in clinic by the Chief Investigator and deemed asymptomatic from the injury, amounting to 111 days between the nine months post-surgery time point and the gait analysis. Table 17 details the duration from the time points that the gait analyses were undertaken.

Table 17 – Fixed bearing (FB) and mobile bearing (MB) patient duration from time points that the gait analyses were undertaken

	FB (days from time point)			MB (days from time point)		
	Mean	SD	Range	Mean	SD	Range
Pre-surgery	-7.40	2.60	3-11	-9.50	6.30	3-17
3 months post-surgery	+9.30	7.30	2-23	+9.10	10.5	0-28
9 months post-surgery	+22.4	39.6	2-111	+11.0	16.8	1-52

'SD' equates to 'Standard deviation'

4.2.1.2. Between-session reliability study

Ten control participants were recruited from advertisements and informal contacts at Northumbria University. Six male and four female participants had a mean age of 25.8 ±2.3yrs, height of 1.75 ±0.1m, mass of 74.17 ±13.11kg, and BMI of 23.99 ±2.49kg/m^2. The inclusion criteria were participants to be aged between 18 to 75 years of age and positive responses to the screening questionnaire (Appendix I). The exclusion criteria were previous knee or hip replacement, current lower limb injury, previous conditions, operations, or other condition which could have had the potential to affect ambulation.

4.2.2 Instrumentation set-up and protocol

4.2.2.1 Within-session reliability study

The instrumentation set-up of the three dimensional motion analysis system was described in Chapter 3 ('3.2 Three dimensional motion analysis system'). Participants undertook a number of walking, stair ascent, stair decent, sit to stand, and stand to sit trials until three trials suitable for analysis were captured as described in Chapter 3 ('3.2.1 Activities of daily living protocol used in the three dimensional motion analysis system').

4.2.2.2 Between-session reliability study

In order to quantify the effect of marker placement error between-sessions, a test-retest design was performed. The instrumentation set-up of the three dimensional motion analysis system was described in Chapter 3 ('3.2 Three dimensional motion analysis system'). Participants undertook a number of walking, stair ascent, and stair decent trials until three trials suitable for analysis were captured as described in Chapter 3 ('3.2.1 Activities of daily living protocol used in the three dimensional motion analysis system'). Following the first testing session, the retroflective markers were removed. The anthropometric measurements were then repeated, with the retroflective markers reattached after a minimum period of an hour in order for skin erythema to subside. The addition of sit to stand and stand to sit trials was not necessary as stair negotiation elicits similar magnitudes of maximum knee flexion and excursion when compared to sitting to standing activities [152, 153]. Only kinematic data were analysed as they are directly related to marker placement. Kinetic data have been previously found to be reliable between-sessions with a negligible source of error [126, 150, 154, 155].

4.2.3 Data analysis

Data cleaning and processing in the three dimensional motion analysis system was undertaken in line with the methods described in Chapter 3 ('3.2.2 Data cleaning and processing in the three dimensional motion analysis system'). Loading ratio for the sit to stand and stand to sit trials in the within-session reliability study was calculated as outlined in Equations 3 and 4.

Equation 3 – Calculation of loading ratio in fixed bearing and mobile bearing total knee replacement patients

$$\text{Total knee replacement patients} = \frac{\text{Maximum force in affected leg}}{\text{Maximum force in contralateral leg}}$$

Equation 4 – Calculation of loading ratio in control participants

$$\text{Control participants} = \frac{\text{Maximum force in nondominant leg}}{\text{Maximum force in dominant leg}}$$

The maximum force is often reached just after lift-off in the sit to stand movement, when the positive vertical acceleration of the participants centre of mass reaches its maximum [156]. In line with the work of Boonstra et al. [156], the 'maximum force' in this study was defined as the maximum value of the normalised vertical ground reaction force (vGRF) from the derivative force curve in Nexus (version 1.7.1, Vicon, Oxford, UK).

The collated biomechanical data for the affected side spatiotemporal, knee kinematic, and knee kinetic variables for walking, stair ascent, and stair decent, in addition to the maximum knee angular velocity and loading ratio of the sit to stand and stand to sit trials, were imported into a Microsoft Excel (Microsoft, Redmond, WA, USA) spreadsheet for the analysis of within-session reliability [157]. Typical error (TE), standardised typical error (STE), Pearson's correlation coefficient *r*, and the intraclass correlation (ICC) were retrieved from the spreadsheet, concurrent with the recommendations of Hopkins [158] for the assessment of reliability.

Typical error, the term preferred by Hopkins [159], describes the standard deviation (SD) in each participant's measurements between trials which is sometimes referred to as the within-participant SD or the standard error of measurement (SEM). This was chosen in preference of other methods, such as the limits of agreement (LOA) approach [160], as the values of LOA depend upon the sample size from which they are estimated, and are therefore biased [158]. Statistical bias can range from <5% when there are more than 25 degrees of freedom (DOF) but rises to 21% for 7 DOF [158]. As the within-session reliability study had 23 DOF, and the between-session study 9 DOF, a resultant statistical bias of 5%-20% would have been present with the use of LOA. The TE, however, has an expected value independent of sample size [158]. Both Bland [161] and Altman [162] have recommended sample sizes of at least 50 participants in order for the sample LOA to be precise estimates of the population LOA, supporting the use of TE in the current study of only 10 participants.

The use of TE when combined with the ICC has been used previously in reliability analyses [131, 163-167], validating the use of the statistic in this thesis.. In addition, authors have also suggested that the reporting of error and the ICC together derive more meaningful interpretations of reliability than the independent use of the ICC [168, 169].

The MDC (Equation 5) for each parameter was also calculated in Microsoft Excel in line with the methods employed by Wilken et al. [170] and Haley and Fragala-Pinkham [171].

Equation 5 – Calculation of the minimum detectable change

$$\mathrm{MDC} = \mathrm{TE} \times 1.96 \times \sqrt{2}$$

In the within-session analysis, three trials for each participant, where possible, were included within the reliability analysis. In some cases, in particular at the pre-surgery time point, patients were only able to perform two trials, or less, during stair ascent and stair descent without using the handrails, or at all. For an experimental group

(FB, MB, and control) to be included within the specific variable reliability analysis, ≥5 of the 8 participants in each group had to present at least two trials in the specific parameter to provide a level of credence to the results and subsequent interpretation.

4.3 Results

4.3.1 Within-session reliability study

4.3.1.1 Spatiotemporal within-session analysis in FB, MB, and controls

4.3.1.1.1 Pre-surgery time point

Walking produced mean STEs interpreted as ‘small’ (0.2<STE<0.6) according to the modified Cohen scale [157]. The mean STE of the FB and control group were ‘small’ during stair stair ascent [157]. The mean STE of the FB group was ‘small’, with the mean of the control group ‘moderate’ (0.6<STE<1.2) during stair descent [157]. An insufficient number of MB patients were able to adequately perform both stair negotiation activities at pre-surgery and were excluded from analysis. Appendix J contains the substantive results of the TE and STE of the spatiotemporal variables at pre-surgery.

All mean ICCs across all groups were concurrent with ‘good’ reliability (≥0.75) in line with the guidelines of Portney and Watkins [172] during walking. The mean FB ICC was ‘moderate’ (0.5<ICC<0.75), with the control group ‘good’ during stair ascent [172]. Upon further inspection, the mean FB ICC was skewed by low correlations in foot off (0.096) and stride length (0.423), with cadence, stride time, and gait velocity all >0.991. Both the mean FB and control group ICCs were ‘moderate’ during stair descent [172]. The mean FB ICC, however, appeared to be skewed by a negative correlation in foot off (-0.186), with the other four variables >0.897 [172]. Appendix K contains the substantive results of the Pearson’s correlation coefficient *r* and the ICC of the spatiotemporal variables at pre-surgery. Table 18 presents the MDC of the spatiotemporal variables in the FB, MB, and control groups at pre-surgery.

Table 18 – Minimum detectable change (MDC) of spatiotemporal variables at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Cadence (steps/min)	20.5	12.1	9.77
Foot off (gait cycle %)	5.62	1.03	2.11
Stride length (m)	0.13	0.11	0.18
Stride time (s)	0.49	0.13	0.07
Gait velocity (m/s)	0.22	0.13	0.22
Stair ascent			
Cadence (steps/min)	1.80	N/A	4.87
Foot off (gait cycle %)	20.4	N/A	3.19
Stride length (m)	0.14	N/A	0.09
Stride time (s)	0.09	N/A	0.06
Gait velocity (m/s)	0.04	N/A	0.22
Stair descent			
Cadence (steps/min)	11.6	N/A	19.9
Foot off (gait cycle %)	30.0	N/A	3.79
Stride length (m)	0.04	N/A	0.06
Stride time (s)	0.45	N/A	0.28
Gait velocity (m/s)	0.06	N/A	0.15

'N/A' equates to 'Not applicable due to there being insufficient data through the participants' inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Due to differences in the measurement units between the spatiotemporal variables, the MDC cannot be discussed as grouped values (Table 18). The data will be used in the following experimental chapter to aid the interpretation of potential biomechanical differences between-groups.

4.3.1.1.2 Three months post-surgery time point

Walking produced 'small' [157] mean STEs across all groups, with stair ascent also producing 'small' [157] mean STEs in the FB and control groups. An insufficient number of MB patients were able to adequately perform the stair ascent activities at three months post-surgery and were excluded from analysis. Stair descent produced 'small' mean STEs in the FB and MB groups, with the control group deriving 'moderate' errors [157]. Appendix L contains the substantive results of the TE and STE of the spatiotemporal variables at three months post-surgery.

The mean ICC of the FB group was 'moderate', with the MB and control groups both considered 'good' [172]. In the FB group, however, both stride length and gait velocity variables were 'good' (>0.947). The mean FB ICC was indicative of ‘moderate’ reliability, with the control group ‘good’ during stair ascent [172]. Cadence, stride length, and gait velocity all exhibited ICCs of >0.828 in the FB group, with the mean skewed by lower correlations in foot off (0.490) and stride time (0.451). The mean ICCs of the FB and MB groups were ‘good’, with the control group ‘moderate’ during stair descent [172]. Appendix M contains the substantive results of the Pearson’s correlation coefficient *r* and the ICC of the spatiotemporal variables at three months post-surgery. Table 19 presents the MDC of the spatiotemporal variables in the FB, MB, and control groups at three months post-surgery.

Table 19 – Minimum detectable change (MDC) of spatiotemporal variables at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Cadence (steps/min)	34.8	10.73	9.77
Foot off (gait cycle %)	6.99	3.83	2.11
Stride length (m)	0.08	0.10	0.18
Stride time (s)	0.61	0.49	0.07
Gait velocity (m/s)	0.11	0.05	0.22
Stair ascent			
Cadence (steps/min)	18.0	N/A	4.87
Foot off (gait cycle %)	5.77	N/A	3.19
Stride length (m)	0.09	N/A	0.09
Stride time (s)	0.92	N/A	0.06
Gait velocity (m/s)	0.10	N/A	0.22
Stair descent			
Cadence (steps/min)	20.4	6.43	19.9
Foot off (gait cycle %)	5.94	5.17	3.79
Stride length (m)	0.08	0.04	0.06
Stride time (s)	0.06	0.39	0.28
Gait velocity (m/s)	0.02	0.05	0.15

‘N/A’ equates to ‘Not applicable due to there being insufficient data through the participants’ inability to adequately perform the required movements (i.e. <5 of each participants in each group)’

4.3.1.1.3 Nine months post-surgery time point

The mean STE of the FB group was ‘moderate’, with the mean error of the MB and control groups ‘small’ in line with the modified Cohen scale during walking [157]. Larger errors in foot off (1.01) and stride time (0.92) were observed in the FB group, contributing to the greater mean. Stair ascent produced ‘small’ [157] mean STEs across all groups. Stair descent produced mean STEs in the FB and MB groups interpreted as ‘small’, with the control group interpreted as ‘moderate’ [157]. Appendix N contains the substantive results of the TE and STE of the spatiotemporal variables at nine months post-surgery.

The mean ICC of the MB and control groups was ‘good’, with the FB group ‘moderate’ [172] during walking. The low mean ICC in the FB group was produced by low magnitudes in cadence, foot off, and stride time; with stride length and gait velocity exhibiting ICC magnitudes that were indicative of ‘good’ reliability [172]. The mean ICC across all groups was ‘good’ during stair ascent [172]. The ICC of all groups was ‘moderate’ during stair descent [172]. The FB and MB groups were skewed by ‘poor’ correlations (<0.50) in foot off and stride length, respectively, with all other variables ‘good’ [172]. Appendix O contains the substantive results of the Pearson’s correlation coefficient *r* and the ICC of the spatiotemporal variables at nine months post-surgery. Table 20 presents the MDC of the spatiotemporal variables in the FB, MB, and control groups at nine months post-surgery.

Table 20 – Minimum detectable change (MDC) of spatiotemporal variables at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Cadence (steps/min)	41.3	10.7	9.77
Foot off (gait cycle %)	6.89	2.64	2.11
Stride length (m)	0.07	0.17	0.18
Stride time (s)	0.74	0.14	0.07
Gait velocity (m/s)	0.09	0.04	0.22
Stair ascent			
Cadence (steps/min)	8.49	7.73	4.87
Foot off (gait cycle %)	4.03	4.80	3.19
Stride length (m)	0.06	0.10	0.09
Stride time (s)	0.22	0.19	0.06
Gait velocity (m/s)	0.11	0.03	0.22
Stair descent			
Cadence (steps/min)	3.40	6.60	19.9
Foot off (gait cycle %)	16.8	4.22	3.79
Stride length (m)	0.07	0.09	0.06
Stride time (s)	1.02	0.22	0.28
Gait velocity (m/s)	0.05	0.04	0.15

4.3.1.1.4 Summary of spatiotemporal within-session analysis in fixed bearing (FB), mobile bearing (MB), and controls at all time points

Table 21 presents a summary of the spatiotemporal variables relating to the STE and the ICC as a mean of walking, stair ascent, and stair descent.

Table 21 – Summary of the standardised typical error (STE) and the intraclass correlation (ICC) as a mean of walking, stair ascent, and stair descent in fixed bearing (FB), mobile bearing (MB), and control participants for the spatiotemporal variables of cadence, foot off, stride length, stride time, and gait velocity. A 'small' STE was defined as 0.2<STE<0.6 [157], a 'moderate' correlation as 0.5<STE<0.75 [172], and a 'good' correlation as ICC≥0.75 [172]

Group	Time point	Reliability parameter	Mean	SD	Result
Fixed bearing	Pre-surgery	STE	0.49	0.06	'small' error
		ICC	0.752	0.080	'good' correlation
	3 months PS	STE	0.51	0.09	'small' error
		ICC	0.730	0.110	'moderate' correlation
	9 months PS	STE	0.46	0.15	'small' error
		ICC	0.723	0.210	'moderate' correlation
Mobile bearing	Pre-surgery	STE	0.3	N/A	'small' error
		ICC	0.937	N/A	'good' correlation
	3 months PS	STE	0.46	0.06	'small' error
		ICC	0.868	0.091	'good' correlation
	9 months PS	STE	0.51	0.03	'small' error
		ICC	0.788	0.044	'good' correlation
Control	N/A	STE	0.52	0.09	'small' error
		ICC	0.756	0.047	'good' correlation

'PS' equates to 'Post-surgery'; 'N/A' to 'Not applicable'; 'SD' to 'Standard deviation'

4.3.1.2 Kinematic within-session analysis in FB, MB, and controls

4.3.1.2.1 Pre-surgery time point

Walking produced 'trivial' (<0.2) mean STEs in the FB and MB groups, with the control group 'small' [157]. Stair ascent produced 'small' mean STEs in the FB and control groups [157]. Stair descent also derived mean STEs interpreted as 'small' in the FB and control groups [157]. An insufficient number of MB patients were able to adequately perform both stair negotiation activities at pre-surgery and were excluded from analysis. Appendix P contains the substantive results of the TE and STE of the kinematic variables at pre-surgery.

Walking produced 'good' [172] mean ICCs across all groups, with the mean FB and control group ICCs 'good' [172] during stair ascent. Both the mean FB and control group ICCs were also interpreted as 'good' during stair descent [172]. Appendix Q contains the substantive results of the Pearson's correlation coefficient *r* and the ICC of the kinematic variables at pre-surgery. Table 22 presents the MDC of the kinematic variables in the FB, MB, and control groups at pre-surgery.

Table 22 – Minimum detectable change (MDC) of knee kinematic variables at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Min knee flexion (°)	1.89	1.35	1.19
Max knee flexion (°)	3.11	6.05	2.85
Sagittal knee ROM (°)	1.91	8.03	3.09
Max knee abduction (°)	2.39	0.95	1.15
Max knee adduction (°)	1.75	1.73	2.43
Frontal knee ROM (°)	2.96	1.22	2.08
Max knee ext. rot. (°)	1.48	1.09	1.98
Max knee int. rot. (°)	2.19	2.20	1.82
Axial knee ROM (°)	2.25	2.92	2.12
Mean	2.21	2.84	2.08
SD	0.54	2.51	0.66
Stair ascent			
Min knee flexion (°)	0.27	N/A	7.91
Max knee flexion (°)	5.69	N/A	2.76
Sagittal knee ROM (°)	2.48	N/A	4.59
Max knee abduction (°)	0.13	N/A	5.32
Max knee adduction (°)	0.26	N/A	10.3
Frontal knee ROM (°)	2.65	N/A	8.71
Max knee ext. rot. (°)	1.49	N/A	7.10
Max knee int. rot. (°)	1.88	N/A	5.26
Axial knee ROM (°)	9.93	N/A	11.0
Mean	2.75	N/A	6.99
SD	3.20	N/A	2.74
Stair descent			
Min knee flexion (°)	0.27	N/A	1.77
Max knee flexion (°)	1.87	N/A	4.36
Sagittal knee ROM (°)	3.44	N/A	4.15
Max knee abduction (°)	0.09	N/A	2.49
Max knee adduction (°)	0.35	N/A	2.79
Frontal knee ROM (°)	1.69	N/A	2.78
Max knee ext. rot. (°)	1.03	N/A	3.61
Max knee int. rot. (°)	0.12	N/A	2.07
Axial knee ROM (°)	1.26	N/A	3.70
Mean	1.12	N/A	3.08
SD	1.10	N/A	0.92

'N/A' equates to 'Not applicable due to there being insufficient data through the participants' inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'; 'SD' to 'Standard deviation'

The mean of all MDC values during walking were less than the clinical threshold of 5° previously used to denote error limits in kinematic analyses [170, 173, 174] (Table 22). The mean MB MDC was skewed by greater magnitudes in maximum knee flexion (6.05°) and sagittal knee ROM (8.03°), with the remaining seven variables <2.93°. In stair ascent, the mean of the FB MDC values was less than the clinical threshold of 5°, with the mean of the control >5°. During stair descent, the mean MDC values of the FB and control groups were less than the clinical threshold of 5°. An insufficient number of MB patients were able to adequately perform both stair negotiation activities at pre-surgery and were excluded.

4.3.1.2.2 Three months post-surgery time point

Walking produced 'small' [157] mean STEs across all groups. The mean STE in the FB group was considered 'trivial', with the control group 'small' during stair ascent [157]. An insufficient number of MB patients were able to adequately perform the stair ascent activities at three months post-surgery and were excluded from analysis. Stair descent produced 'small' [157] mean STEs across all groups. Appendix R contains the substantive results of the TE and STE of the kinematic variables at three months post-surgery.

All mean ICCs across all groups were interpreted as 'good' during walking [172]. The mean FB and control group ICCs were 'good' during stair ascent [172]. Both the mean FB and control group ICCs were 'good', with the MB group 'moderate' during stair descent [172]. Appendix S contains the substantive results of the Pearson's correlation coefficient *r* and the ICC of the kinematic variables at three months post-surgery. Table 23 presents the MDC of the kinematic variables in the FB, MB, and control groups at three months post-surgery.

Table 23 – Minimum detectable change (MDC) of knee kinematic variables at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Min knee flexion (°)	1.74	1.28	1.19
Max knee flexion (°)	3.68	1.83	2.85
Sagittal knee ROM (°)	3.68	2.87	3.09
Max knee abduction (°)	4.06	1.84	1.15
Max knee adduction (°)	8.39	5.83	2.43
Frontal knee ROM (°)	5.47	4.66	2.08
Max knee ext. rot. (°)	7.15	4.38	1.98
Max knee int. rot. (°)	3.04	3.39	1.82
Axial knee ROM (°)	3.83	4.11	2.12
Mean	4.56	3.35	2.08
SD	2.09	1.53	0.66
Stair ascent			
Min knee flexion (°)	2.66	N/A	7.91
Max knee flexion (°)	2.36	N/A	2.76
Sagittal knee ROM (°)	3.23	N/A	4.59
Max knee abduction (°)	2.05	N/A	5.32
Max knee adduction (°)	3.00	N/A	10.3
Frontal knee ROM (°)	3.05	N/A	8.71
Max knee ext. rot. (°)	2.30	N/A	7.10
Max knee int. rot. (°)	2.18	N/A	5.26
Axial knee ROM (°)	1.58	N/A	11.0
Mean	2.49	N/A	6.99
SD	0.54	N/A	2.74
Stair descent			
Min knee flexion (°)	0.84	0.37	1.77
Max knee flexion (°)	3.17	1.99	4.36
Sagittal knee ROM (°)	3.37	0.62	4.15
Max knee abduction (°)	0.19	0.59	2.49
Max knee adduction (°)	1.33	1.99	2.79
Frontal knee ROM (°)	2.73	6.10	2.78
Max knee ext. rot. (°)	0.16	2.38	3.61
Max knee int. rot. (°)	0.49	0.53	2.07
Axial knee ROM (°)	0.74	6.91	3.70
Mean	1.45	2.39	3.08
SD	1.29	2.46	0.92

'N/A' equates to 'Not applicable due to there being insufficient data through the participants' inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'; 'SD' to 'Standard deviation'

The mean of all MDC values were less than the clinical threshold of 5° previously used to denote error limits in kinematic analyses during walking [170, 173, 174] (Table 23). The mean of the FB MDC values were less than the clinical threshold of 5°, with the mean of the control group >5° during stair ascent. During stair descent, the mean MDC of all three groups was also <5°.

4.3.1.2.3 Nine months post-surgery time point

Walking produced mean STEs in the FB and control groups that were considered 'small', with the MB group 'trivial' [157]. Stair ascent produced 'trivial' mean STEs, with the FB and control groups 'small' [157]. Stair descent produced mean STEs in all groups that were considered 'small' [157]. Appendix T contains the substantive results of the TE and STE of the kinematic variables at nine months post-surgery.

Mean ICCs across all groups were 'good' during walking, stair ascent, and stair descent [172]. Appendix U contains the substantive results of the Pearson's correlation coefficient *r* and the ICC of the kinematic variables at nine months post-surgery. Table 24 presents the MDC of the kinematic variables in the FB, MB, and control groups at nine months post-surgery.

Table 24 – Minimum detectable change (MDC) of knee kinematic variables at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
<u>Walking</u>			
Min knee flexion (°)	1.99	1.15	1.19
Max knee flexion (°)	1.26	2.49	2.85
Sagittal knee ROM (°)	2.45	2.75	3.09
Max knee abduction (°)	0.90	1.16	1.15
Max knee adduction (°)	1.57	1.35	2.43
Frontal knee ROM (°)	2.34	1.86	2.08
Max knee ext. rot. (°)	3.04	1.40	1.98
Max knee int. rot. (°)	2.82	2.37	1.82
Axial knee ROM (°)	2.99	3.12	2.12
Mean	2.15	1.96	2.08
SD	0.77	0.74	0.66
<u>Stair ascent</u>			
Min knee flexion (°)	2.23	1.43	7.91
Max knee flexion (°)	2.21	2.92	2.76
Sagittal knee ROM (°)	2.21	3.99	4.59
Max knee abduction (°)	0.96	1.71	5.32
Max knee adduction (°)	1.17	2.23	10.3
Frontal knee ROM (°)	1.74	3.36	8.71
Max knee ext. rot. (°)	2.44	1.43	7.10
Max knee int. rot. (°)	3.72	2.62	5.26
Axial knee ROM (°)	4.50	5.28	11.0
Mean	2.35	2.77	6.99
SD	1.13	1.28	2.74
<u>Stair descent</u>			
Min knee flexion (°)	0.75	1.35	1.77
Max knee flexion (°)	0.25	1.57	4.36
Sagittal knee ROM (°)	0.99	2.69	4.15
Max knee abduction (°)	0.17	5.48	2.49
Max knee adduction (°)	0.04	1.91	2.79
Frontal knee ROM (°)	0.33	4.59	2.78
Max knee ext. rot. (°)	0.16	4.18	3.61
Max knee int. rot. (°)	7.58	4.38	2.07
Axial knee ROM (°)	11.0	3.18	3.70
Mean	2.36	3.26	3.08
SD	4.03	1.48	0.92

'SD' equates to 'Standard deviation'

The mean of all MDC values during walking and stair descent were less than the clinical threshold of 5° previously used to indicate error limits in kinematic analyses [170, 173, 174] (Table 24). During stair ascent, the mean of the FB and MB MDC values were also <5°, with the mean of the control group >5°.

4.3.1.2.4 Summary of kinematic within-session analysis in fixed bearing (FB), mobile bearing (MB), and controls at all time points

Table 24 presents a summary of the kinematic variables relating to the STE and the ICC as a mean of walking, stair ascent, and stair descent.

Table 25 – Summary of the standardised typical error (STE) and the intraclass correlation (ICC) as a mean of walking, stair ascent, and stair descent in fixed bearing (FB), mobile bearing (MB), and control participants for the knee kinematic variables of minimum knee flexion angle, maximum knee flexion angle, sagittal knee ROM, maximum knee abduction, maximum knee adduction, frontal knee ROM, maximum knee external rotation, maximum knee internal rotation, and axial knee ROM. A 'trivial' error was defined as <0.2, a 'small' error as 0.2<STE<0.6 [157], and a 'good' correlation as ICC≥0.75 [172]

Group	Time point	Reliability parameter	Mean	SD	Result
Fixed bearing	Pre-surgery	STE	0.24	0.1	'small' error
		ICC	0.945	0.043	'good' correlation
	3 months PS	STE	0.21	0.06	'small' error
		ICC	0.975	0.160	'good' correlation
	9 months PS	STE	0.2	0.07	'small' error
		ICC	0.935	0.087	'good' correlation
Mobile bearing	Pre-surgery	STE	0.16	N/A	'trivial' error
		ICC	0.976	N/A	'good' correlation
	3 months PS	STE	0.35	0.07	'small' error
		ICC	0.829	0.130	'good' correlation
	9 months PS	STE	0.24	0.06	'small' error
		ICC	0.961	0.170	'good' correlation
Control	N/A	STE	0.32	0.09	'small' error
		ICC	0.912	0.080	'good' correlation

'PS' equates to 'Post-surgery'; 'N/A' to 'Not applicable'; 'SD' to 'Standard deviation'

4.3.1.3Kinetic within-session analysis in FB, MB, and controls

4.3.1.3.1 Pre-surgery time point

Walking produced 'small' [157] mean STEs across all groups. The mean STE of the FB and control groups were 'small' during stair ascent and stair descent [157]. An insufficient number of MB patients, however, were able to adequately perform both stair negotiation activities at pre-surgery and were excluded from analysis. Appendix V contains the substantive results of the TE and STE of the kinetic variables at pre-surgery.

All groups during walking produced mean ICCs that were interpreted as ‘good’ [172]. During stair negotiation, the FB and control groups were ‘good’. Appendix W contains the substantive results of the Pearson’s correlation coefficient *r* and the ICC of the kinetic variables at pre-surgery. Table 26 presents the MDC of the kinetic variables in the FB, MB, and control groups at pre-surgery.

Table 26 – Minimum detectable change (MDC) of knee kinetic variables at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Max knee ext. mom (Nm/kg)	0.57	0.54	0.80
Max knee flx. mom (Nm/kg)	1.14	1.42	1.56
Knee flx at max ext. mom (°)	3.75	17.0	4.22
Knee flx at max flx. mom (°)	5.75	4.78	2.01
Max knee ab. mom (Nm/kg)	0.33	0.32	0.41
Max knee add. mom (Nm/kg)	0.68	1.02	0.80
Max knee ext. mom (Nm/kg)	0.10	0.38	0.22
Max knee int. mom (Nm/kg)	0.25	0.65	0.32
Stair ascent			
Max knee ext. mom (Nm/kg)	0.16	N/A	1.00
Max knee flx. mom (Nm/kg)	0.12	N/A	0.92
Knee flx at max ext. mom (°)	64.9	N/A	6.54
Knee flx at max flx. mom (°)	2.66	N/A	15.1
Max knee ab. mom (Nm/kg)	0.27	N/A	0.48
Max knee add. mom (Nm/kg)	0.61	N/A	0.76
Max knee ext. mom (Nm/kg)	0.01	N/A	0.15
Max knee int. mom (Nm/kg)	0.01	N/A	0.45
Stair descent			
Max knee ext. mom (Nm/kg)	0.43	N/A	1.03
Max knee flx. mom (Nm/kg)	0.90	N/A	1.27
Knee flx at max ext. mom (°)	58.8	N/A	8.80
Knee flx at max flx. mom (°)	38.1	N/A	32.4
Max knee ab. mom (Nm/kg)	0.63	N/A	0.47
Max knee add. mom (Nm/kg)	0.46	N/A	0.73
Max knee ext. mom (Nm/kg)	0.31	N/A	0.25
Max knee int. mom (Nm/kg)	0.36	N/A	0.41

‘N/A’ equates to ‘Not applicable due to there being insufficient data through the participants’ inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)’

Due to differences in the measurement units between the kinetic variables, the MDC cannot be discussed as grouped values. The data will be used in the following experimental chapter to aid the interpretation of potential biomechanical differences between-groups.

4.3.1.3.2 Three months post-surgery time point

The mean STE of the FB group was ‘trivial’, with the mean of the MB and control groups ‘small’ during walking [157]. The mean STE in the FB and control groups was ‘small’ during stair ascent [157]. An insufficient number of MB patients were able to adequately perform the stair ascent activity at three months post-surgery and were therefore excluded. The mean STE of all three groups was ‘small’ during stair descent [157]. Appendix X contains the substantive results of the TE and STE of the kinetic variables at three months post-surgery.

Mean ICCs across all groups were ‘good’ during walking and stair descent [172]. In addition, the FB and control groups were indicative of ‘good’ reliability during stair ascent [172]. Appendix Y contains the substantive results of the Pearson’s correlation coefficient *r* and the ICC of the kinetic variables at three months post-surgery. Table 27 presents the MDC of the kinetic variables in the FB, MB, and control groups at three months post-surgery.

Table 27 – Minimum detectable change (MDC) of knee kinetic variables at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Max knee ext. mom (Nm/kg)	0.34	0.11	0.80
Max knee flx. mom (Nm/kg)	0.68	0.29	1.56
Knee flx at max ext. mom (°)	2.71	2.43	4.22
Knee flx at max flx. mom (°)	3.10	1.56	2.01
Max knee ab. mom (Nm/kg)	0.24	0.08	0.41
Max knee add. mom (Nm/kg)	0.36	0.19	0.80
Max knee ext. mom (Nm/kg)	0.12	0.05	0.22
Max knee int. mom (Nm/kg)	0.09	0.15	0.32
Stair ascent			
Max knee ext. mom (Nm/kg)	0.90	N/A	1.00
Max knee flx. mom (Nm/kg)	1.95	N/A	0.92
Knee flx at max ext. mom (°)	51.7	N/A	6.54
Knee flx at max flx. mom (°)	9.24	N/A	15.1
Max knee ab. mom (Nm/kg)	0.56	N/A	0.48
Max knee add. mom (Nm/kg)	0.77	N/A	0.76
Max knee ext. mom (Nm/kg)	0.26	N/A	0.15
Max knee int. mom (Nm/kg)	0.45	N/A	0.45
Stair descent			
Max knee ext. mom (Nm/kg)	0.42	0.55	1.03
Max knee flx. mom (Nm/kg)	0.06	0.27	1.27
Knee flx at max ext. mom (°)	10.0	11.5	8.80
Knee flx at max flx. mom (°)	20.5	11.2	32.4
Max knee ab. mom (Nm/kg)	0.73	0.13	0.47
Max knee add. mom (Nm/kg)	0.07	0.42	0.73
Max knee ext. mom (Nm/kg)	0.27	0.02	0.25
Max knee int. mom (Nm/kg)	0.09	0.11	0.41

'N/A' equates to 'Not applicable due to there being insufficient data through the participants' inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'; 'SD' to 'Standard deviation'

4.3.1.3.3 Nine months post-surgery time point

Walking, stair ascent, and stair descent all produced 'small' mean STEs across all groups [157]. Appendix Z contains the substantive results of the TE and STE of the kinetic variables at nine months post-surgery.

The mean ICC across all groups during walking, stair ascent, and stair descent was indicative of 'good' reliability [172]. Appendix AA contains the substantive results of the Pearson's correlation coefficient *r* and the ICC of the kinetic variables at nine months post-surgery. Table 28 presents the MDC of the kinetic variables in the FB, MB, and control groups at nine months post-surgery.

Table 28 – Minimum detectable change (MDC) of knee kinetic variables at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Walking			
Max knee ext. mom (Nm/kg)	0.05	0.25	0.80
Max knee flx. mom (Nm/kg)	0.12	0.16	1.56
Knee flx at max ext. mom (°)	7.13	1.67	4.22
Knee flx at max flx. mom (°)	23.2	23.8	2.01
Max knee ab. mom (Nm/kg)	0.02	0.07	0.41
Max knee add. mom (Nm/kg)	0.02	0.17	0.80
Max knee ext. mom (Nm/kg)	0.01	0.02	0.22
Max knee int. mom (Nm/kg)	0.03	0.06	0.32
Stair ascent			
Max knee ext. mom (Nm/kg)	0.09	0.08	1.00
Max knee flx. mom (Nm/kg)	0.12	0.10	0.92
Knee flx at max ext. mom (°)	59.6	33.4	6.54
Knee flx at max flx. mom (°)	41.9	20.6	15.1
Max knee ab. mom (Nm/kg)	0.04	0.03	0.48
Max knee add. mom (Nm/kg)	0.11	0.08	0.76
Max knee ext. mom (Nm/kg)	0.02	0.02	0.15
Max knee int. mom (Nm/kg)	0.04	0.04	0.45
Stair descent			
Max knee ext. mom (Nm/kg)	0.03	0.13	1.03
Max knee flx. mom (Nm/kg)	0.03	0.05	1.27
Knee flx at max ext. mom (°)	6.88	4.74	8.80
Knee flx at max flx. mom (°)	40.3	30.8	32.4
Max knee ab. mom (Nm/kg)	0.00	0.30	0.47
Max knee add. mom (Nm/kg)	0.04	0.23	0.73
Max knee ext. mom (Nm/kg)	0.03	0.13	0.25
Max knee int. mom (Nm/kg)	0.04	0.07	0.41

4.3.1.3.4 Summary of kinetic within-session analysis in fixed bearing (FB), mobile bearing (MB), and controls at all time points

Table 29 presents a summary of the kinetic variables relating to the STE and the ICC as a mean of walking, stair ascent, and stair descent.

Table 29 – Summary of the standardised typical error (STE) and the intraclass correlation (ICC) as a mean of walking, stair ascent, and stair descent in fixed bearing (FB), mobile bearing (MB), and control participants for the knee kinetic variables of maximum knee extension moment, maximum knee flexion moment, knee flexion at maximum knee extension moment, knee flexion at maximum knee flexion moment, maximum knee abduction moment, maximum knee adduction moment, maximum knee external rotation moment, and maximum knee internal rotation moment. A 'small' STE was defined as 0.2<STE<0.6 [157], and a 'good' correlation as ICC≥0.75 [172]

Group	Time point	Reliability parameter	Mean	SD	Result
Fixed bearing	Pre-surgery	STE	0.3	0.09	'small' error
		ICC	0.879	0.083	'good' correlation
	3 months PS	STE	0.34	0.13	'small' error
		ICC	0.893	0.064	'good' correlation
	9 months PS	STE	0.4	0.03	'small' error
		ICC	0.817	0.035	'good' correlation
Mobile bearing	Pre-surgery	STE	0.28	N/A	'small' error
		ICC	0.931	N/A	'good' correlation
	3 months PS	STE	0.26	0.08	'small' error
		ICC	0.958	0.016	'good' correlation
	9 months PS	STE	0.27	0.02	'small' error
		ICC	0.866	0.051	'good' correlation
Control	N/A	STE	0.38	0.07	'small' error
		ICC	0.890	0.061	'good' correlation

'PS' equates to 'Post-surgery'; 'N/A' to 'Not applicable'; 'SD' to 'Standard deviation'

4.3.1.4 Maximum knee angular velocity and loading ratio within-session analysis in FB, MB, and controls

4.3.1.4.1 Pre-surgery time point

Sit to stand produced a 'small' [157] mean STE across both variables. The mean STE of the FB and control groups was considered 'small' [157], with the MB group 'moderate' during stand to sit [157]. Appendix AB contains the substantive results of the TE and STE of the maximum knee angular velocity and loading ratio variables at pre-surgery.

Mean ICCs across all groups were interpreted as 'good' during sit to stand [172]. During stand to sit, the mean ICC of the FB group was 'good', with the MB and control groups 'moderate' [172]. Appendix AC contains the substantive results of the Pearson's correlation coefficient *r* and the ICC of the maximum knee angular velocity and loading ratio variables at pre-surgery. Table 30 presents the MDC of the maximum knee angular velocity and loading ratio variables in the FB, MB, and control groups at pre-surgery.

Table 30 – Minimum detectable change (MDC) of maximum knee angular displacement velocity and loading ratio variables at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Sit to stand			
Max knee extension velocity (°/s)	18.5	9.65	19.6
Loading ratio	0.22	0.08	0.14
Stand to sit			
Max knee flexion velocity (°/s)	23.4	24.8	15.1
Loading ratio	0.16	0.23	0.29

Due to differences in the measurement units between the variables, the MDC cannot be discussed as grouped values (Table 30). The data will be used in the following experimental chapter to aid the interpretation of potential biomechanical differences between-groups.

4.3.1.4.2 Three months post-surgery time point

The mean STE of the FB and control groups was 'small' during both sit to stand and stand to sit [157]. At three months post-surgery, an insufficient number of MB patients were able to adequately perform the sit to stand and stand to sit activities, and were therefore excluded from analysis. Appendix AD contains the substantive results of the TE and STE of the maximum knee angular velocity and loading ratio variables at three months post-surgery.

The FB ICC was 'moderate', with the control group 'good' across both variables during sit to stand [172]. During stand to sit, the mean ICC of the FB and control groups was 'moderate' [172]. Appendix AE contains the substantive results of the Pearson's correlation coefficient *r* and the ICC of the maximum knee angular velocity and loading ratio variables at three months post-surgery. Table 31 presents the MDC of the maximum knee angular velocity and loading ratio variables in the FB, MB, and control groups at three months post-surgery.

Table 31 – Minimum detectable change (MDC) of maximum knee angular displacement velocity and loading ratio variables at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Sit to stand			
Max knee ext velocity (°/s)	10.3	N/A	19.6
Loading ratio	0.38	N/A	0.14
Stand to sit			
Max knee flx velocity (°/s)	13.6	N/A	15.1
Loading ratio	0.41	N/A	0.29

'N/A' equates to 'Not applicable due to there being insufficient data through the participants' inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

4.3.1.4.3 Nine months post-surgery time point

The mean STE of all groups was 'small' during sit to stand [157]. During stand to sit, the mean STE of the FB and MB groups was 'small' [157], with the control group 'moderate' [157]. Appendix AF contains the substantive results of the TE and STE of the maximum knee angular velocity and loading ratio variables at nine months post-surgery.

The mean ICC across all groups was 'good' during sit to stand [172]. The mean ICC of the FB and control groups was 'moderate', with the MB group 'good' during stand to sit [172]. Appendix AG contains the substantive results of the Pearson's correlation coefficient *r* and the ICC of the maximum knee angular velocity and loading ratio variables at three months post-surgery. Table 32 presents the MDC of the maximum knee angular velocity and loading ratio variables in the FB, MB, and control groups at nine months post-surgery.

Table 32 – Minimum detectable change (MDC) of maximum knee angular displacement velocity and loading ratio variables at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants

	Fixed bearing	Mobile bearing	Control
Sit to stand			
Max knee ext velocity (°/s)	22.4	31.0	19.6
Loading ratio	0.20	0.30	0.14
Stand to sit			
Max knee flx velocity (°/s)	27.5	27.4	15.1
Loading ratio	0.42	0.14	0.29

4.3.1.4.4 Summary of maximum knee angular velocity and loading ratio within-session analysis in fixed bearing (FB), mobile bearing (MB), and controls at all time points

Table 33 presents a summary of the maximum knee angular velocity and loading ratio variables relating to the STE and the ICC as a mean of sit to stand and stand to sit trials.

Table 33 – Summary of the standardised typical error (STE) and the intraclass correlation (ICC) as a mean of walking, stair ascent, and stair descent in fixed bearing (FB), mobile bearing (MB), and control participants for the maximum knee angular velocity and loading ratio variables during sit to stand and stand to sit trials. A 'small' error was defined as 0.2<STE<0.6 [157], a 'moderate' correlation as 0.5<STE<0.75, and a 'good' correlation as ICC≥0.75 [172]

Group	Time point	Reliability parameter	Mean	SD	Result
Fixed bearing	Pre-surgery	STE	0.42	0.11	'small' error
		ICC	0.868	0.08	'good' correlation
	3 months PS	STE	0.59	0.01	'small' error
		ICC	0.638	0.044	'moderate' correlation
	9 months PS	STE	0.54	0.07	'small' error
		ICC	0.758	0.145	'good' correlation
Mobile bearing	Pre-surgery	STE	0.44	0.33	'small' error
		ICC	0.810	0.247	'good' correlation
	3 months PS	STE	N/A	N/A	N/A
		ICC	N/A	N/A	N/A
	9 months PS	STE	0.37	0.09	'small' error
		ICC	0.894	0.074	'good' correlation
Control	N/A	STE	0.45	0.26	'small' error
		ICC	0.779	0.264	'good' correlation

'PS' equates to 'Post-surgery'; 'N/A' to 'Not applicable'; 'SD' to 'Standard deviation'

4.3.2 Between-session reliability study

Walking produced a mean STE interpreted as 'small' across the knee kinematic variables [157]. The greatest variability was observed in the minimum knee flexion angle, derving a STE of 0.8 and classified as 'moderate' [157]. All other STEs were <0.49 and thus 'small'. Similar results were found in stair ascent and stair descent with the mean STE 'small' across the knee kinematic variables [157].

A mean ICC of 0.84 ±0.17 was found across the combined knee kinematic variables during walking and indicative of 'good' reliability [172]. Similar findings of 'good' reliability were observed in stair ascent (0.75 ±0.26) and stair descent (0.88 ±0.08), although stair ascent was skewed by low correlations in the axial plane kinematic variables of maximum knee external rotation (0.39 ±0.37) and maximum knee internal rotation (0.22 ±0.53). Appendix AJ contains the substantive results of the TE, STE, Pearson's correlation coefficient *r*, and the ICC of the knee kinematic variables. Table 34 presents the MDC of the knee kinematic variables in the control group.

Table 34 – Between-session Minimum detectable change (MDC) of knee kinematic variables in control participants

	Control
Walking	
Min knee flexion (°)	3.66
Max knee flexion (°)	4.68
Sagittal knee ROM (°)	4.81
Max knee abduction (°)	1.95
Max knee adduction (°)	5.74
Frontal knee ROM (°)	6.22
Max knee ext. rot. (°)	8.60
Max knee int. rot. (°)	7.82
Axial knee ROM (°)	4.94
Mean	4.94
SD	2.36
Stair ascent	
Min knee flexion (°)	4.99
Max knee flexion (°)	3.93
Sagittal knee ROM (°)	6.25
Max knee abduction (°)	6.94
Max knee adduction (°)	7.59
Frontal knee ROM (°)	7.35
Max knee ext. rot. (°)	9.48
Max knee int. rot. (°)	9.65
Axial knee ROM (°)	7.50
Mean	7.07
SD	1.87
Stair descent	
Min knee flexion (°)	3.49
Max knee flexion (°)	2.47
Sagittal knee ROM (°)	3.64
Max knee abduction (°)	7.02
Max knee adduction (°)	7.81
Frontal knee ROM (°)	4.86
Max knee ext. rot. (°)	9.06
Max knee int. rot. (°)	9.42
Axial knee ROM (°)	7.43
Mean	6.13
SD	2.57

'SD' equates to 'Standard deviation'

The mean MDC of the combined values during walking were less than the clinical threshold of 5° previously used to indicate error limits in kinematic analyses [170, 173,

[174] (Table 34). During stair ascent the mean MDC was >5°, although when the axial plane knee kinematic variables were excluded, the mean reduced to 6.17 ±1.44° from 7.07 ±1.87°. Similar findings were observed in stair descent, with the exclusion of the axial plane knee kinematic variables reducing the mean to less than the clinical threshold of 5° (4.88 ±2.12°).

4.4 Discussion

The main finding across the within-session collated spatiotemporal, knee kinematic, and knee kinetic variables was that of small errors and high correlations. In the spatiotemporal variables, STEs that were 'small' in magnitude [157] and ICCs indicative of 'good' reliability [172] were found in patients before TKR surgery and controls during walking.

In previous research assessing within-session reliability of spatiotemporal variables, Fransen et al. [175] analysed OA populations during walking, documenting reliability indices for gait velocity, cadence, and stride length. The authors found ICCs ranging from 0.90-0.98, with greater variability in gait velocity trials performed at a normal walking speed, although no differences were observed in cadence and stride length. Lower collated ICCs were found in the current study, with a mean of 0.752 ±0.08 in the FB group, 0.937 in the MB group, and 0.756 ±0.047 in the control group encompassing cadence, foot off percentage, stride length, stride time, and gait velocity. These differences can be partly explained by the mean being skewed by low correlations in foot off and stride length in the FB group, with cadence, stride time, and gait velocity exhibiting magnitudes of >0.991. Methodological explanations for these differences are also apparent, with Fransen et al. [175] utilising five trials in analysis compared to three in the current study. Monaghan et al. [176] and Diss et al. [177] found increased reliability in controls with the inclusion of more trials, with the authors advocating the use of ten and five trials for minimising variance, respectively. This was not appropriate in the current study due to the considerable symptomatic burden experienced by the patients, in particular at pre-surgery, but also at three months post-surgery. For the inclusion of three trials in the current study, patients were typically undertaking six or more walks along the length of the walkway in order to capture a trial where the entire foot was within the boundaries of the force plate. From the available evidence, the use of three trials is not optimal, but the findings of this study have shown that results indicative of good reliability can be obtained in a symptomatic population. Studies have also demonstrated that reliability continues to decrease with fewer trials, with Maynard et al. [178] and Noonan et al. [179] including only one trial in analysis. The findings of Beckerman et al. [180], however, support the use of three trials, with the authors concluding that two or more repeated trials are preferable in minimising the measurement error.

A finding of note in the FB group was reduced reliability when compared to the MB group at three and nine months post-surgery in the spatiotemporal variables. The patients randomised to FB and MB groups in the current study were well matched at baseline with regards to demographic variables. Both groups followed the same post-surgery rehabilitation program which was standard care at the time of testing, although adherence to this was not monitored for the purposes of this study and may have been a contributing factor. In addition, differences between FB and MB groups in kinematic and kinetic variables may have accounted for this, although this study was limited to reliability analyses. There were also no substantial differences in the reliability of kinematic and kinetic data which could have influenced the spatiotemporal data.

In the more biomechanically demanding activities of stair negotiation [181, 182], the control group exhibited both ‘moderate’ STEs [157] and ICC magnitudes [172] during stair descent, with the FB group also exhibiting a ‘moderate’ ICC [172] during stair negotiation in the spatiotemporal variables. This greater variability during stair negotiation can likely be explained by the greater biomechanical demands of the activity when compared to walking. This includes the requirement for greater angles [183], ROM [184], forces [181, 185], moments [186], and powers [187].

Within the spatiotemporal variables in the FB group during stair ascent at the pre-surgery time point, a low correlation in foot off percentage (-0.186) was identified. This low correlation likely represents the difficulty associated with undertaking stair ascent using a ‘step over step’ technique, without the use of supportive handrails in this population suffering from late stage knee OA. The high variability of the foot off percentage infers the adoption of potentially different compensatory strategies within-patients in order to endure the combined effects of their symptomatic burden and the demands of the activity. The stair ascending technique utilised within this thesis is also unlikely to be undertaken by the patients during free living conditions at the pre-surgery time point due to their symptomatic burden. It has been noted that OA and TKR patients prefer the use a ‘step-by-step’ technique [182], although this was not employed in this thesis as only a ‘step over step’ technique allowed the measurement of ground reaction forces in the presence of one force plate in the stair rig. This potential unfamiliarity with the technique may have also contributed to the high variability observed in this instance.

A further potential explanation for the spatiotemporal differences was the position of the force plate as the first step in the instrumented stair rig. Yu et al. [188] found that joint mechanics collected for initial steps were more variable in comparison to steps further from the ground. These factors may have reduced the within-session reliability, however, the effect across the patient groups was equal as the data were collected on the same stair rig configuration using the same protocol, thus introducing no between-group methodological differences [189]. Another potential contributing factor was that the second initial contact of the gait cycle (100% of gait cycle) was not identified by the vGRF due to having only one integrated force plate in the instrumented stair rig. The use of marker trajectories to determine the second initial contact, therefore, may have been indicative of greater error. Despite this concern, stride time exhibited a consistently ‘good’ ICC [172] during all time points, suggesting no substantial variability in the use of marker trajectories.

The within-session knee kinematic data produced consistently ‘trivial’ and ‘small’ STEs [157] and ICCs indicative of ‘good’ reliability [172] across all participant groups, time points, and activities. Only the MB group produced ICCs suggesting ‘moderate’ reliability [172] during stair descent at three months post-surgery. Stair descent is regarded as a more biomechanically demanding activity than stair ascent, despite similar sagittal knee kinematics [184, 190, 191], due to the requirement for substantial eccentric quadriceps activity [192, 193]. This, coupled with the reduced number of MB patients able to adequately perform the activity at three months post-surgery when compared to FB patients, provides a possible explanation as to why lower reliability indices were found.

Few authors have analysed within-session or between-session reliability of kinematic data in orthopaedic populations [131, 194], with Ornetti et al. [195] concluding that the available data are insufficient. The results of the current study suggest that the intrinsic variations in the kinematic data were stable within a single session [196]. No previous authors have presented kinematic MDC magnitudes for OA or TKR patients, although the MDC has been previously defined in controls for a range of kinematic variables during walking [170], with a clinical threshold of 5° used to indicate error limits [173, 174]. The MDC of within-session kinematic variables for walking in FB and MB groups were predominately <5°, with few exceptions. Lower MDC magnitudes were found in maximum knee flexion and sagittal knee ROM across all groups when compared to Wilken et al. [170]. The comparable relevance of this to the within-session analysis of the current study is questionable, as Wilken et al. [170] only assessed between-session reliability which includes the effect of extrinsic variations such as marker placement and anthropometric measurements, in addition to only including controls.

The greatest magnitudes of MDC in the current study were observed in the frontal and axial planes, with values reaching approximately 10° in the axial plane knee ROM in the FB group during stair ascent (9.93°) at pre-surgery, in the FB group during stair descent at nine months post-surgery (10.99°), and in the control group during stair ascent (10.98°). Wilken et al. [170] only presented sagittal knee kinematics, although values in excess of 7° during maximum knee flexion were found. It has been suggested that displacements in the frontal and axial planes are subject to greater errors than the sagittal plane, in particular, measurements at the hip and knee [126, 194, 197, 198]. The lower reliability of knee kinematics in the frontal and axial planes may be partially explained by the smaller ROM of the knee in these planes compared to the noise of the data [194], thus increasing the standardised difference.

Similar findings of 'trivial' and 'small' errors [157], in addition to 'good' ICCs [172] across all groups, time points, and activities were exhibited in the knee kinetic variables. Within the orthopaedic literature, considerable interest has been shown in determining the reliability of the maximum knee adduction moment [165, 199], with previous work identifying the variable as a valid determinant for the dynamic load acting on the medial compartment of the knee [200, 201]. Birmingham et al. [165] found a mean difference between-sessions of 0.1%BW*Ht (LCI=0.1%BW*Ht, UCI=0.3%BW*Ht), deriving an ICC of 0.86 (LCI=0.73, UCI=0.96), suggesting good between-session reliability in patients awaiting high tibial osteotomy. Andrews et al. [199] assessed controls and found no difference in the analysis of variance between-sessions for each participant, with the results deriving a pooled SD variability of 0.43%BW*Ht. A greater ICC was found in the current study compared to Birmingham et al. [165], although both authors assessed between-session reliability which probably accounts for the lower reliability observed. Kadaba et al. [126] also found that when participants walked at a natural speed the knee abduction and adduction moments were repeatable, with a coefficient of multiple correlation of 0.95 for within-session and 0.90 between-session reliability, respectively. The authors concluded that it is reasonable to base clinical decisions on the results of a single gait evaluation, with the results of the current study supporting this assertion.

The sit to stand and stand to sit activities produced ‘small’ to ‘moderate’ STEs [157], with ‘good’ to ‘moderate’ ICCs [172] in the within-session analysis. The loading ratio at three months post-surgery was somewhat variable, with moderate ICCs in the FB group during both sit to stand and stand to sit. This increased variability was potentially casued by a combination of the biomechanical difficulty of the activities and the compromised rehabilitation status of patients at three months post-surgery. The reliability increased at nine months post-surgery following an adequate period of rehabilitation [99, 100], supporting this assertion.

The reliability of sit to stand activities have been investigated previously [202, 203]. Jeng et al. [202] measured kinematic data and found ICCs indicating ‘good’ [172] reliability in knee angular displacements (0.93 ±0.12). Hanke et al. [203] assessed the reliability of the centre of mass during sit to stand, reporting ICCs of ≥0.81 for all speeds of movement between-sessions, although no kinetic variables specific to this study were investigated. Previous authors have measured the loading ratio as undertaken in the current study [156, 204-206], although no reliability data were presented.

In a cohort of control participants, an additional between-session analysis was undertaken to determine the error in the positioning of the reflective markers, the primary cause of extrinsic variation in gait analyses [176]. This was undertaken to aid the interpretation of between-group and within-group analyses of FB and MB groups in Chapters 5 and 6.

Standardised typical errors indicative of ‘small’ errors [157] and ICCs suggestive of ‘good’ reliability [172] were found across walking, stair ascent, and stair descent. Sit to stand and stand to sit activities were not investigated as they have been shown to exhibit similar magnitudes of motion to stair negotiation at the knee [152, 190, 191], and would therefore not provide additional information.

The results of the current study were in agreement with Maynard et al. [178] who found good between-session reliability of knee kinematic variables. The authors also assessed the reliability of hip kinematic variables, finding poor reliability. This is consistent with previous observations [207], and could be due to the easier identification of the anatomical landmarks for the placement of markers on the knee, with typically less subcutaneous tissue.

Unsurprisingly, lower reliability was found when compared to the within-session analysis. The effect of marker removal and reapplication has been shown to previously account for 75% [151] and 90% [208] of error between-sessions. This has been demonstrated in a study by Groen et al. [209] who found that lateral epicondyle marker placement of 10mm in antero-posterior and infero-superior directions resulted in errors greater than the normal variability range during gait analyses.

Similar MDC magnitudes were derived in the current study when compared to Wilken et al. [170], with values of 4.68° in maximum knee flexion and 4.81° in sagittal knee ROM compared to 7.33° and 5.08° in Wilken et al. [170], respectively, during walking. The similarities between the data can be explained by the use of a comparable asymptomatic participant cohort, age, and gender distribution, although different motion analysis systems were used. The subtle differences between instrumentation support the requirement for identifying laboratory specific MDC values to ensure appropriate data interpretation. The results of the MDC analysis suggest repeatable between-session measurements within previously defined limits for sagittal knee kinematics [170, 173, 174].

Similar to the within-session analysis, displacements in the frontal and axial planes exhibited greater errors and subsequent MDC magnitudes compared to the sagittal plane kinematics. In a similar manner to the within-session analyses, this is potentially caused by the smaller ROM at the knee in these planes compared to the noise of the data [194]. Consultation of the MDC magnitudes for specific variables must therefore be undertaken to aid the interpretation of potential between-group differences in Chapters 5 and 6.

4.4.2 Limitations

In both the within-session and between-session analyses, the analysis was limited to the affected side in the TKR patients, with the right side analysed in the controls. Only the affected knee was of specific interest in thesis as the patients had unilateral knee OA and thus received unilateral implantation of a total knee prosthesis. Previous studies have also limited analyses to the affected knee when determining the effect of prosthetic design on knee biomechanics [10, 29, 77-79]. Despite only analysing the right side of controls in the current study, it has been previously determined that reliability for kinematic and kinetic variables is comparable between left and right sides [210].

Ethical issues prevented the blinding of patients following surgery relating to which prosthesis they received. Although not as important in this chapter concerning reliability, this could have potentially influenced patient behaviour [211]. It has been previously found that randomised trials that have not used appropriate blinding methods show larger treatment effects than blinded studies [212]. This effect is typically raised in subjective data [211], with the current study specific to objective biomechanical data only. This is unlikely, therefore, to have had any considerable effect on the analyses presented in the current study.

A potential limitation of the study is that all activities were undertaken at a self-selected velocity, and therefore not standardised. There is debate in the literature concerning whether to control for gait velocity [213], with some authors employing the use of fast walking speeds [170, 175]. The majority of authors, however, have analysed the reliability of gait at a self-selected velocity [131, 163, 165, 178, 194, 214], the method employed in this thesis. Further, in a systematic review concerning the reliability of gait analysis measurements, McGinley et al. [215] found that 12 studies reported data at a self-selected velocity, with only one study using a fixed speed of running. The rationale for using a self-selected velocity was to capture a normal representation of movement. It was also identified in Chapter 2 that self-selected velocity was used in previous work comparing FB and MB prostheses by means of gait analysis [10, 29, 77-80]. As such, utilising the same method in this instance allows important cross study comparisons to be made in an area that is under researched [9].

A limitation of the between-session analysis is that participants were used with a lower BMI than the FB and MB groups, with both patient groups classified as obese category one (30-34.99kg/m^2) [216]. Despite the well-recognised limitations of the BMI measurement, it is not unreasonable to assume that the TKR patients had a greater body fat percentage, making them potentially more susceptible to greater skin tissue artefact (STA) errors in motion analyses [217]. It is difficult, however, to reduce STA errors within motion analysis using non-invasive methods due to the absence of a regular consistent pattern of STA [217-220]. In the current study, the anatomical sites for marker attachment were over bony anatomical landmarks, whereby typically, the thickness of the subcutaneous layer is reduced. This is likely to negate any substantial effects between patients and controls due to differences in BMI.

It is also important to consider that error in the measurement of spatiotemporal, kinematic, and kinetic variables can be caused by numerous confounding variables. Among the participants tested, factors that were not controlled for in the current study include stature, pain intensity, level of cardiovascular fitness and endurance, severity of symptoms, and potential within-surgeon variance in surgical technique. The MDC as a measure of responsiveness is impacted upon by sample variance and therefore may be overestimated in conditions where potential confounding variables are not controlled for [163]. The minimum control of some sources of variance does, however, increase the study's external and ecological validity due to the relatively small sample size.

4.5 Conclusions

- There was found to be good overall within-session reliability in kinematic and kinetic data, with some findings of moderate reliability in spatiotemporal variables.
- There was found to be good between-session reliability of sagittal plane kinematic variables, with MDC values less than the previously defined error limits in kinematic analyses. Lower reliability was evident in the frontal and axial planes.
- MDC values were presented for the within-session analyses to aid the interpretation of between-group differences in the subsequent chapters. MDC values were also presented for the kinematic between-session analysis to determine and control for the effect of marker placement errors between FB and MB groups in Chapters 5 and 6.

5.0 Biomechanical analysis of fixed bearing and mobile bearing total knee replacement patients during walking

5.1 Introduction

Following the determination of the within-session and between-session reliability, in addition to the calculation of minimum detectable change (MDC) magnitudes in Chapter 4, fixed bearing (FB) and mobile bearing (MB) total knee replacement (TKR) patients were compared during walking in a comparative analysis.

From the available literature in Chapter 2, Mockel et al. [78] and Kramers-de Quervain et al. [80] presented results in favour of MB prostheses during walking that warrant further investigation [14]. Mockel et al. [78] found increased stance phase knee flexion in MB knees (14.1°) when compared to FB knees (10.8°), an indication of a more effective shock-absorbing mechanism during the loading response of the stance phase of the gait cycle [221]. This is similar to the normal knee, and deviates from the ‘quadriceps avoidance gait’ often associated with TKR [115].

Kramers-de Quervain et al. [80] detailed greater maximum knee flexion during the swing phase of gait in MB knees (52.4 ±7.56°) when compared to FB knees (47.1 ±4.74°) in bilaterally implanted TKR patients. A greater maximum knee flexion during swing demonstrates an improved ability for limb advancement and foot-clearance [221], in addition to increasing overall range of movement (ROM) which is an important determinant of function after TKR surgery [118].

The aim of this study was to analyse whether MB total knee prostheses offer biomechanical advantages compared to FB designs during walking. This chapter, in part, has been published in the Bone and Joint Journal (Appendix A) and The Knee (Appendix C).

5.2 Method

5.2.1 A priori power calculation

A power calculation was undertaken at the study outset. Based on an effect size (Cohen's *f*) of 0.35 ((≥0.25 - <0.40 = medium [113]), an α error probability of 0.05, and a power (1-β error probability) of 0.8, in addition to three groups with three measurement periods in a within-between interaction; a total sample size of 21 was derived (FB, MB, and control groups combined). G*Power (Version 3.1.2, Dr Franz Faul et al., Heinrich Heine Universität, Dusseldorf, Germany) was used to undertake the calculation [222, 223]. Figure 12 depicts the power as a function of the sample size.

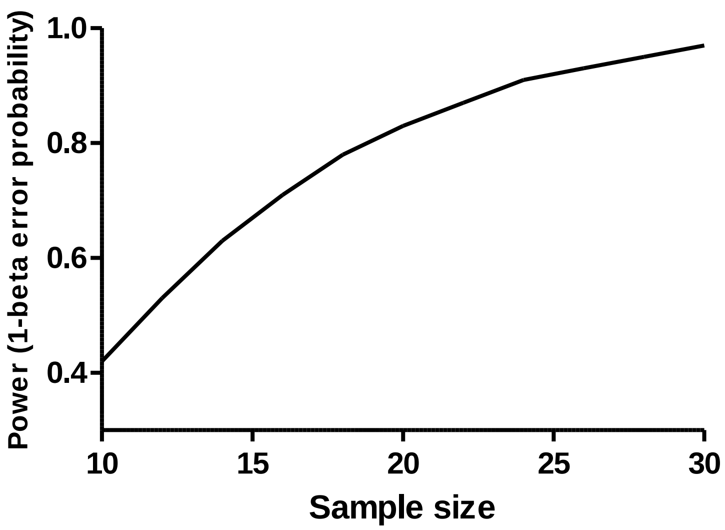

Figure 10 – Power (1-beta error probability) as a function of sample size from the power calculation. The calculation was based on an effect size (Cohen's *f*) of 0.35 ((≥0.25 - <0.40 = medium [113]) and an α error probability of 0.05

5.2.2 Participants

The patient cohort described in Chapter 4 ('4.2.1 Participants') was used in this study, in addition to the age and gender matched controls. The surgical procedure and post-surgery rehabilitation protocol was detailed in Chapter 3 ('3.4 Surgical procedure').

5.2.3 Instrumentation set-up and protocol

Gait analyses were undertaken in the FB and MB groups at pre-surgery, three months post-surgery, and nine months post-surgery, in addition to a single testing session for the age and gender matched controls as described in Chapter 3 ('3.2.1 Activities of daily living protocol used in the three dimensional motion analysis system').

A 12 camera three dimensional motion analysis system (MX, Vicon, Oxford, UK) and integrated force plates (OR6-7, AMTI, Watertown MA, USA) were calibrated and set-up using the methods detailed in Chapter 3 ('3.2 Three dimensional motion analysis system').

5.2.4 Data analysis

A post-hoc power analysis using G*Power (Version 3.1.2, Dr Franz Faul et al., Heinrich Heine Universität, Dusseldorf, Germany) was performed [222, 223]. Using a Cohen's *f* effect size of 0.35 (($\geq$0.25 - <0.40 = medium [113]), an alpha error probability of 0.05, a total sample of 24, and three groups with three repeated measures achieved a power of 0.91.

Data cleaning and processing in the three dimensional motion analysis system was undertaken in line with the methods described in Chapter 3 ('3.2.2 Data cleaning and processing in the three dimensional motion analysis system').

5.2.4.1Participant demographics and anthropometry

Normality of distribution was checked by calculating skewness and kurtosis in order to verify the assumptions of the ANOVA parametric tests in PASW Statistics (Version 18, Chicago, IL, USA). Skewness and kurtosis were converted to z-scores in line with the recommendations of Field [224]. The conversion is detailed in Equation 6 and Equation 7 for skewness and kurtosis, respectively.

Equation 6 – Converting skewness to a z-score

$$\text{z skewness} = \frac{\text{skewness} - \text{mean}}{\text{SE} \times \text{skewness}}$$

- 'SE' equates to 'standard error'

Equation 7 – Converting kurtosis to a z-score

$$z \text{ kurtosis} = \frac{\text{kurtosis} - \text{mean}}{\text{SE} \times \text{kurtosis}}$$

The resultant z-score was indicative of a normal distribution if the magnitude was <1.96. A magnitude of >1.96 was significant at the 0.05 level, and a magnitude of >2.58 was significant at the 0.01 level. The Kolmogorov-Smirnov test and Shapiro-Wilk test were also undertaken to verify data normality. The data were considered not significantly different to a normal distribution if p>0.05. To determine if there were significant differences in the demographic data between-groups, a one way ANOVA was undertaken. Levene's test was used to establish the variance in the three groups. The ANOVA was accepted if the Levene's test was not significant (p>0.05). A post-hoc Tukey test was used to determine between-group differences if the ANOVA was significant (p<0.05). All data were considered to be normally distributed.

5.2.4.2 Patient Oxford Knee Score

The original version of the Oxford Knee Score (OKS) developed by Dawson et al. [225] was utilised. This uses a scoring system ranging from 12 to 60, where a lower score indicates better function. Data normality was tested using the same method as that described in section '5.2.4.1 Participant demographics and anthropometry'. A two way repeated measures ANOVA was undertaken to analyse differences between-groups (FB, MB), and also between pre-surgery, three months post-surgery, and nine months post-surgery time points. Mauchly's test for sphericity was undertaken to determine whether the assumption of sphericity was met. Sphericity was assumed if Mauchly's test was not significant (p>0.05). In data where sphericity was not assumed, the violations were adjusted for by using the Greenhouse-Geisser correction. If the ANOVA was significant for 'group' or 'time point' (p<0.05), post-hoc pairwise comparisons with the Bonferroni method for the adjustment of multiple comparisons were undertaken. This was accepted in both spherical and non-spherical data, as the method has been shown to be robust when sphericity is violated, as well as being the suggested test to optimise statistical power in smaller samples [224].

5.2.4.3 Participant spatiotemporal, kinematic, and kinetic variables

Data normality was tested using the same method as that described in section '5.2.4.1 Participant demographics and anthropometry'. A two way repeated measures ANOVA was undertaken to analyse differences between-groups (FB, MB, control), and also between pre-surgery, three months post-surgery, and nine months post-surgery time points. The same procedure as outlined in '5.2.4.2 Patient Oxford Knee Score' was utilised to test for sphericity. If the ANOVA was significant for 'group' or 'time point' (p<0.05), post-hoc pairwise comparisons with the Bonferroni method for the adjustment of multiple comparisons were undertaken. Gabriel's pairwise test was used in data where the sample sizes were uneven [224].

5.3 Results

5.3.1 Participant anthropometry

Table 35 presents the between-group analysis of the anthropometric details.

Table 35 – Between fixed bearing (FB), mobile bearing (MB), and control group differences in anthropometric variables

	Between-group effects		Tukey post-hoc multiple comparisons		
			FB-Control	MB-Control	FB-MB
	Sig.	F	*p* value	*p* value	*p* value
Age (yrs)	p = 0.96	0.05	-	-	-
Height (m)	p = 0.65	0.44	-	-	-
Mass (kg)	**p < 0.05**	4.73	0.07	**p< 0.05**	0.86
BMI (kg/m^2)	**p < 0.05**	3.86	0.06	0.06	1.00

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'

No differences were observed between-groups in age (FB = 59.3 ±8.80yrs; MB = 59.6 ±7.70yrs; Control = 60.5 ±7.00yrs; $F_{2,21}$ = 0.05; p=0.96) or height (FB = 1.66 ±0.09m; MB = 1.70 ±0.09m; Control = 1.67 ±0.12m; $F_{2,21}$ = 0.44; p=0.65) (Table 35). Significance was reached in the ANOVA relating to mass between-groups (FB = 87.9 ±16.1kg; MB = 91.2 ±12.4kg; Control = 72.6 ±9.43kg; $F_{2,21}$ = 4.73; p<0.05), with the MB group heavier than the control group ($F_{2,21}$ = 4.73; p<0.05). No differences were observed between FB and MB groups.

5.3.2 Oxford Knee Score

Pairwise comparisons are presented in Table 36 relating to the differences between FB and MB groups in the Oxford Knee Score (OKS) at pre-surgery, three months post-surgery, and nine months post-surgery. Table 37 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups relating to the OKS.

Table 36 – Fixed bearing (FB) and mobile bearing (MB) between-group differences in the Oxford Knee Score (OKS) at pre-surgery, three months post-surgery, and nine months post-surgery time point

	FB		MB		Group		FB-MB
	Mean	SD	Mean	SD	Sig.	F	*p* value
Pre-surgery	39.0	7.64	37.4	5.32	*p* = 0.89	0.02	-
Three months post-surgery	25.9	12.2	24.5	9.62	*p* = 0.89	0.02	-
Nine months post-surgery	19.6	5.65	21.1	9.53	*p* = 0.89	0.02	-

‘SD’ equates to ‘Standard deviation’; ‘Sig.’ to ‘Significance of ANOVA’; F’ to ‘F statistic’

The FB group had an OKS of 37.75 ±7.91 at pre-surgery, 25.88 ±12.18 at three months post-surgery, and 19.57 ±5.65 at nine months post-surgery (Table 36). The MB group had an OKS of 37.43 ±5.32 at pre-surgery, 24.50 ±9.62 at three months post-surgery, and 20.13 ±9.28 at nine months post-surgery. No differences ($F_{1,19}$ = 0.02; p=0.89) were observed between FB and MB groups at pre-surgery, three months post-surgery, or nine months post-surgery.

Table 37 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences in the Oxford Knee Score (OKS) between fixed bearing (FB) and mobile bearing (MB) patients

	Time point		Pre-3PS	3PS-9PS	Pre-9PS
	Sig.	F	*p* value	*p* value	*p* value
FB	**p < 0.05**	26.0	**p< 0.05**	$p = 0.59$	**p< 0.05**
MB	**p < 0.05**	26.0	**p< 0.05**	$p = 1.00$	**p< 0.05**

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic; 'PS' to 'Post-surgery'

Differences were observed in the within-group between time point analysis (Table 37). The FB group had a reduced OKS between pre-surgery and three months post-surgery ($F_{2,24} = 26.0$; $p<0.05$), and between pre-surgery and nine months post-surgery ($F_{2,24} = 26.0$; $p<0.05$) in the post-hoc pairwise comparisons. The MB group also presented reductions between pre-surgery and three months post-surgery ($F_{2,24} = 26.0$; $p<0.05$), and between pre-surgery and nine months post-surgery ($F_{2,24} = 26.0$; $p<0.05$).

At pre-surgery, the mean OKS of both FB and MB groups was indicative of 'moderate to severe osteoarthritis' (31-40). Both groups exhibited 'mild to moderate' osteoarthritis (21-30) at three months post-surgery. At nine months post-surgery, the FB group was indicative of 'satisfactory joint function' (12-20) and the MB group to 'mild to moderate' osteoarthritis (21-30) [225], although there were little differences in the mean scores (FB=19.6 ±5.65; MB=21.1 ±9.53).

5.3.3 Spatiotemporal

Pairwise comparisons are presented in Table 38 relating to the differences between FB, MB, and control groups in spatiotemporal variables at pre-surgery, three months post-surgery, and nine months post-surgery. Table 39 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the spatiotemporal variables.

Table 38 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of spatiotemporal variables at pre-surgery, three months post-surgery, and nine months post-surgery time points

Level walking		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Cadence (steps/min)	101	22.4	89.6	9.64	120	14.1	$\boldsymbol{p < 0.05}$	12.7	0.10	*	0.74
	Foot off (gait cycle %)	61.2	4.02	60.1	1.49	60.5	1.21	$p = 0.08$	2.76	-	-	-
	Stride length (m)	1.05	0.15	1.13	0.20	1.30	0.10	$\boldsymbol{p < 0.05}$	12.5	*	0.16	1.00
	Stride time (s)	1.25	0.31	1.32	0.17	1.01	0.11	$\boldsymbol{p < 0.05}$	10.8	0.11	*	1.00
	Gait velocity (m/s)	0.89	0.26	0.87	0.20	1.29	0.11	$\boldsymbol{p < 0.05}$	33.2	*	*	1.00
Three months post-surgery	Cadence (steps/min)	99.0	18.7	92.4	10.7	120	14.1	$\boldsymbol{p < 0.05}$	12.7	*	*	1.00
	Foot off (gait cycle %)	61.8	2.02	61.9	2.25	60.5	1.21	$p = 0.08$	2.76	-	-	-
	Stride length (m)	1.08	0.12	1.10	0.21	1.30	0.10	$\boldsymbol{p < 0.05}$	12.5	*	0.06	1.00
	Stride time (s)	1.27	0.30	1.26	0.22	1.01	0.11	$\boldsymbol{p < 0.05}$	10.8	0.09	0.14	1.00
	Gait velocity (m/s)	0.93	0.22	0.85	0.21	1.29	0.11	$\boldsymbol{p < 0.05}$	33.2	*	*	1.00
Nine months post-surgery	Cadence (steps/min)	101	16.9	96.3	10.1	120	14.1	$\boldsymbol{p < 0.05}$	12.7	0.05	*	1.00
	Foot off (gait cycle %)	63.1	1.79	61.6	0.80	60.5	1.21	$p = 0.08$	2.76	-	-	-
	Stride length (m)	1.11	0.13	1.23	0.09	1.30	0.10	$\boldsymbol{p < 0.05}$	12.5	*	0.71	0.23
	Stride time (s)	1.25	0.25	1.23	0.12	1.01	0.11	$\boldsymbol{p < 0.05}$	10.8	*	0.08	1.00
	Gait velocity (m/s)	1.01	0.21	1.00	0.12	1.29	0.11	$\boldsymbol{p < 0.05}$	33.2	*	*	1.00

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'

Table 39 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of spatiotemporal variables in fixed bearing (FB) and mobile bearing (MB) patients

Level walking		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Cadence (steps/min)	$p = 0.47$	0.63	-	-	-
	Foot off (gait cycle %)	$p = 0.13$	2.34	-	-	-
	Stride length (m)	$p = 0.07$	2.87	-	-	-
	Stride time (s)	$p = 0.71$	0.26	-	-	-
	Gait velocity (m/s)	$\boldsymbol{p < 0.05}$	4.39	1.00	0.48	0.13
MB	Cadence (steps/min)	$p = 0.47$	0.63	-	-	-
	Foot off (gait cycle %)	$p = 0.13$	2.34	-	-	-
	Stride length (m)	$p = 0.07$	2.87	-	-	-
	Stride time (s)	$p = 0.71$	0.26	-	-	-
	Gait velocity (m/s)	$\boldsymbol{p < 0.05}$	4.39	1.00	0.05	0.13

‘Sig.’ equates to ‘Significance of ANOVA’; ‘F’ to ‘F statistic’; ‘PS’ to ‘Post-surgery’

At pre-surgery, reductions were found in the FB group when compared to controls in stride length ($F_{1.46,26.28} = 12.5$; $p<0.05$) and gait velocity ($F_{1.33,23.92} = 33.2$; $p<0.05$) (Table 38). Similar findings were apparent in the MB group with a reduction in gait velocity ($F_{1.33,23.92} = 33.2$; $p<0.05$), but also a reduction in cadence ($F_{1.46,26.21} = 12.7$; $p<0.05$), and an increase in stride time ($F_{1.27,22.83} = 10.8$; $p<0.05$) when compared to controls. No differences were observed between FB and MB groups at pre-surgery.

Similar findings were apparent at three months post-surgery. Reductions were observed in the FB group when compared to controls in stride length ($F_{1.46,26.28} = 12.5$; $p<0.05$), gait velocity ($F_{1.33,23.92} = 33.2$; $p<0.05$), and cadence ($F_{1.46,26.21} = 12.7$; $p<0.05$). The MB group was also found to walk with reduced cadence ($F_{1.46,26.21} = 12.7$; $p<0.05$) and gait velocity ($F_{1.33,23.92} = 33.2$; $p<0.05$) than controls. No differences were found between FB and MB groups at three months post-surgery.

The FB group walked with reduced stride length ($F_{1.46,26.28} = 12.5$; $p<0.05$), gait velocity ($F_{1.33,23.92} = 33.2$; $p<0.05$), and stride time ($F_{1.27,22.83} = 10.8$; $p<0.05$) when compared to controls at nine months post-surgery. The MB group derived similar results to those at three months post-surgery, with reductions in cadence ($F_{1.46,26.21} =$

12.7; $p<0.05$) and gait velocity ($F_{1.33,23.92} = 33.2$; $p<0.05$). No differences were observed between FB and MB groups at nine months post-surgery.

In the within-group and between time point analysis, the ANOVA only reached significance in gait velocity ($F_{2,36} = 4.39$; $p<0.05$), with no differences in the pairwise comparisons (Table 39).

5.3.4 Knee kinematic

Continuous waveforms of the sagittal knee kinematics are presented in Figure 11 for the FB, MB, and control groups at pre-surgery, three months post-surgery, and nine months post-surgery. Pairwise comparisons are presented in Table 40 relating to the differences between FB, MB, and control groups in kinematic variables at pre-surgery, three months post-surgery, and nine months post-surgery. Table 41 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery time points in FB and MB groups, relating to the kinematic variables.

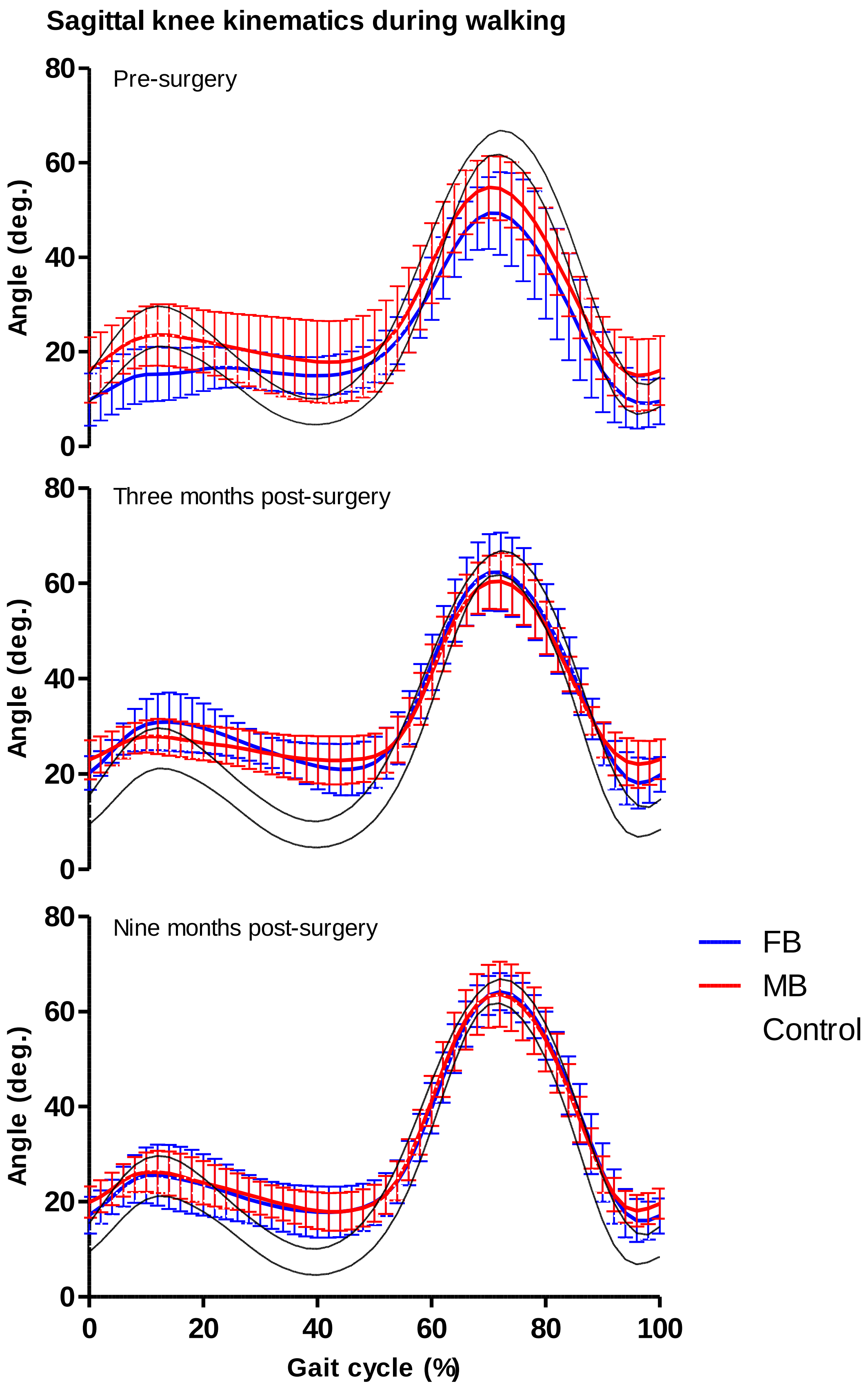

Figure 11 – Gait cycle percentage normalised continuous waveforms of the sagittal knee kinematics for the fixed bearing, mobile bearing, and control groups at pre-surgery, three months post-surgery, and nine months post-surgery. Error bars represent 95% confidence intervals. The white area between the black lines represents the 95% confidence interval range for the control group

Table 40 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of kinematic variables at pre-surgery, three months post-surgery, and nine months post-surgery time points

Level walking		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Min knee flexion (°)	12.9	10.2	13.2	10.5	6.18	3.16	$\boldsymbol{p < 0.05}$	17.5	0.42	0.38	1.00
	Max knee flexion (°)	54.8	10.7	54.8	9.85	64.2	2.74	$p = 0.06$	3.00	-	-	-
	Sagittal knee ROM (°)	41.9	9.08	41.6	8.38	58.0	3.73	$\boldsymbol{p < 0.05}$	22.9	*	*	1.00
	Max knee abduction (°)	-6.53	14.1	-3.53	10.3	-7.11	7.58	$p = 0.17$	1.98	-	-	-
	Max knee adduction (°)	8.39	13.5	5.34	11.7	7.41	5.83	$\boldsymbol{p < 0.05}$	4.85	1.00	1.00	1.00
	Frontal knee ROM (°)	14.9	4.02	8.87	4.82	14.5	3.39	$\boldsymbol{p < 0.05}$	9.04	1.00	*	*
	Max knee external rotation (°)	-7.84	8.79	-10.7	3.80	-12.0	15.9	$p = 0.51$	0.68	-	-	-
	Max knee internal rotation (°)	3.51	7.42	0.56	4.16	3.76	15.9	$p = 0.58$	0.56	-	-	-
	Axial knee ROM (°)	11.4	3.22	11.2	3.32	15.8	3.52	$p = 0.33$	1.14	-	-	-
Three months post-surgery	Min knee flexion (°)	17.9	5.46	20.9	5.49	6.18	3.16	$\boldsymbol{p < 0.05}$	17.5	*	*	0.75
	Max knee flexion (°)	61.0	10.7	60.9	5.84	64.2	2.74	$p = 0.06$	3.00	-	-	-
	Sagittal knee ROM (°)	43.1	10.9	40.0	9.71	58.0	3.73	$\boldsymbol{p < 0.05}$	22.9	*	*	1.00
	Max knee abduction (°)	-13.6	9.6	-16.8	6.07	-7.11	7.58	$p = 0.17$	1.98	-	-	-
	Max knee adduction (°)	-0.63	11.8	-5.80	8.00	7.41	5.83	$\boldsymbol{p < 0.05}$	4.85	0.28	*	0.85
	Frontal knee ROM (°)	13.0	5.44	11.0	2.78	14.5	3.39	$\boldsymbol{p < 0.05}$	9.04	1.00	0.31	1.00
	Max knee external rotation (°)	-11.0	10.3	-11.8	5.50	-12.0	15.9	$p = 0.51$	0.68	-	-	-
	Max knee internal rotation (°)	3.88	11.0	5.55	3.26	3.76	15.9	$p = 0.58$	0.56	-	-	-
	Axial knee ROM (°)	14.8	5.07	17.3	5.06	15.8	3.52	$p = 0.33$	1.14	-	-	-
Nine months post-surgery	Min knee flexion (°)	14.5	5.26	17.0	4.45	6.18	3.16	$\boldsymbol{p < 0.05}$	17.5	*	*	0.90
	Max knee flexion (°)	64.0	4.02	63.8	7.75	64.2	2.74	$p = 0.06$	3.00	-	-	-
	Sagittal knee ROM (°)	49.5	6.62	46.8	9.41	58.0	3.73	$\boldsymbol{p < 0.05}$	22.9	0.08	*	1.00
	Max knee abduction (°)	-13.9	12.9	-11.1	6.57	-7.11	7.58	$p = 0.17$	1.98	-	-	-
	Max knee adduction (°)	1.82	11.9	-1.64	4.89	7.41	5.83	$\boldsymbol{p < 0.05}$	4.85	0.59	0.13	1.00
	Frontal knee ROM (°)	15.8	7.03	9.43	2.22	14.5	3.39	$\boldsymbol{p < 0.05}$	9.04	1.00	0.14	0.06
	Max knee external rotation (°)	-6.62	13.7	-15.5	5.15	-12.0	15.9	$p = 0.51$	0.68	-	-	-
	Max knee internal rotation (°)	9.87	15.9	1.89	7.30	3.76	15.9	$p = 0.58$	0.56	-	-	-
	Axial knee ROM (°)	16.5	4.48	17.4	5.01	15.8	3.52	$p = 0.33$	1.14	-	-	-

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'

Table 41 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of kinematic variables in fixed bearing (FB) and mobile bearing (MB) patients

Level walking		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Min knee flexion (°)	$p = 0.06$	3.67	-	-	-
	Max knee flexion (°)	$\boldsymbol{p < 0.05}$	7.18	0.18	0.91	*
	Sagittal knee ROM (°)	$\boldsymbol{p < 0.05}$	3.66	1.00	0.28	*
	Max knee abduction (°)	$\boldsymbol{p < 0.05}$	11.5	*	1.00	0.08
	Max knee adduction (°)	$\boldsymbol{p < 0.05}$	8.31	*	0.44	0.28
	Frontal knee ROM (°)	$p = 0.81$	0.12	-	-	-
	Max knee external rotation (°)	$p = 0.64$	0.46	-	-	-
	Max knee internal rotation (°)	$p = 0.35$	1.09	-	-	-
	Axial knee ROM (°)	$\boldsymbol{p < 0.05}$	6.79	0.20	1.00	0.05
MB	Min knee flexion (°)	$p = 0.06$	3.67	-	-	-
	Max knee flexion (°)	$\boldsymbol{p < 0.05}$	7.18	0.20	0.94	*
	Sagittal knee ROM (°)	$\boldsymbol{p < 0.05}$	3.66	1.00	0.22	0.21
	Max knee abduction (°)	$\boldsymbol{p < 0.05}$	11.5	*	*	0.07
	Max knee adduction (°)	$\boldsymbol{p < 0.05}$	8.31	*	0.06	0.22
	Frontal knee ROM (°)	$p = 0.81$	0.12	-	-	-
	Max knee external rotation (°)	$p = 0.64$	0.46	-	-	-
	Max knee internal rotation (°)	$p = 0.35$	1.09	-	-	-
	Axial knee ROM (°)	$\boldsymbol{p < 0.05}$	6.79	*	1.00	*

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; '*' to 'significant at the 0.05'; 'PS' to 'Post-surgery'

No differences were observed outside of the 95% confidence intervals between FB and MB groups across the continuous waveforms (Figure 11). At pre-surgery, the FB and MB groups walked with reduced knee flexion, outside of the 95% confidence intervals, during the mid-swing phase of the gait cycle (70%-72%) compared to controls. At three months post-surgery, greater knee flexion was observed in the FB and MB groups, with no differences around mid-swing observed when compared to controls. Both FB and MB groups walked with greater knee flexion during mid and terminal stance phase than controls, a difference outside of the 95% confidence intervals. Comparable knee flexion during mid-swing was observed in the FB and MB groups compared to controls at nine months post-surgery, a pattern similar to that observed at three months post-surgery. Both FB and MB groups walked with greater knee flexion during mid and terminal stance phase than controls, a difference outside of the 95% confidence intervals, although not to the extent observed at three months post-surgery.

In the discrete variables, reductions were found across both FB ($F_{2,38} = 22.9$; $p<0.05$) and MB ($F_{2,38} = 22.9$; $p<0.05$) groups in sagittal ROM when compared to controls at pre-surgery (Table 40). The MB group was found to exhibit a reduced frontal knee ROM ($F_{2,38}$ = 9.04; p<0.05) compared to controls. The MB group was also found to walk with a reduced frontal knee ROM ($F_{2,38}$ = 9.04; p<0.05) than the FB group (FB=14.9 ±4.02°; MB=8.87 ±4.82°). At three months post-surgery, both the FB ($F_{1.36,25.82}$ = 3.00; p<0.05) and MB groups ($F_{1.36,25.82}$ = 3.00; p<0.05) walked with a greater minimum knee flexion than controls. Both FB ($F_{2,38}$ = 22.9; p<0.05) and MB ($F_{2,38}$ = 22.9; p<0.05) groups exhibited a reduction in sagittal knee ROM when compared to controls. No differences were observed between FB and MB groups. The FB ($F_{1.36,25.82}$ = 3.00; p<0.05) and MB ($F_{1.36,25.82}$ = 3.00; p<0.05) groups walked with greater minimum knee flexion angles than controls at nine months post-surgery. The MB group also exhibited a reduced sagittal knee ROM ($F_{2,38}$ = 22.9; p<0.05) when compared to controls. No differences were observed between FB and MB groups.

In the FB group, maximum knee abduction ($F_{2,38}$ = 11.5; p<0.05) increased from pre-surgery to three months post-surgery, with the maximum knee adduction angle ($F_{1.29,24.57}$ = 8.31: p<0.05) reducing between the time points (Table 41). From pre-surgery to nine months post-surgery, maximum knee flexion ($F_{2,38}$ = 7.18; p<0.05) and sagittal knee ROM increased ($F_{2,38}$ = 3.66; p<0.05). The MB group also exhibited an increase in maximum knee abduction ($F_{2,38}$ = 11.5; p<0.05) and maximum knee adduction ($F_{1.29,24.57}$ = 8.31; p<0.05) from pre-surgery to three months post-surgery. In addition, axial knee ROM ($F_{2,38}$ = 6.79; p<0.05) increased between the two time points. From three months post-surgery to nine months post-surgery, maximum knee abduction reduced ($F_{2,38}$ = 11.5; p<0.05). Both maximum knee flexion ($F_{2,38}$ = 7.18; p<0.05) and axial knee ROM ($F_{2,38}$ = 6.79; p<0.05) increased from pre-surgery to nine months post-surgery.

5.3.5 Knee kinetic

Pairwise comparisons are presented in Table 42 relating to the differences between FB, MB, and control groups in kinetic variables at pre-surgery, three months post-surgery, and nine months post-surgery. Table 43 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the kinetic variables.

Table 42 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of kinetic variables at pre-surgery, three months post-surgery, and nine months post-surgery time points

Level walking		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Max knee ext. moment (Nm/kg)	-0.28	0.15	-0.25	0.04	-0.39	0.05	***p* < 0.05**	11.0	0.08	*	1.00
	Max knee flx. moment (Nm/kg)	0.54	0.35	0.49	0.29	0.96	0.30	***p* < 0.05**	8.26	0.05	*	1.00
	Knee flx at max ext. moment (°)	14.0	10.3	14.8	10.9	11.0	3.89	***p* < 0.05**	7.80	1.00	1.00	1.00
	Knee flx at max flx. moment (°)	26.7	11.6	24.4	8.79	25.5	5.57	*p* = 0.61	0.40	-	-	-
	Max knee ab. moment (Nm/kg)	-0.13	0.19	-0.06	0.05	-0.11	0.04	*p* = 0.98	0.03	-	-	-
	Max knee add. moment (Nm/kg)	0.44	0.13	0.40	0.17	0.46	0.13	***p* < 0.05**	9.20	1.00	1.00	1.00
	Max knee ext. rot. moment (Nm/kg)	-0.01	0.00	-0.02	0.02	-0.02	0.01	*p* = 0.20	1.74	-	-	-
	Max knee int. rot. moment (Nm/kg)	0.14	0.09	0.13	0.06	0.17	0.04	*p* = 0.28	1.24	-	-	-
Three months post-surgery	Max knee ext. moment (Nm/kg)	-0.23	0.11	-0.25	0.08	-0.39	0.05	***p* < 0.05**	11.0	*	*	1.00
	Max knee flx. moment (Nm/kg)	0.58	0.40	0.77	0.18	0.96	0.30	***p* < 0.05**	8.26	0.09	0.82	0.86
	Knee flx at max ext. moment (°)	19.8	6.57	23.5	5.33	11.0	3.89	***p* < 0.05**	7.80	*	*	0.66
	Knee flx at max flx. moment (°)	28.3	5.65	28.3	5.25	25.5	5.57	*p* = 0.61	0.40	-	-	-
	Max knee ab. moment (Nm/kg)	-0.10	0.07	-0.14	0.13	-0.11	0.04	*p* = 0.98	0.03	-	-	-
	Max knee add. moment (Nm/kg)	0.22	0.08	0.24	0.15	0.46	0.13	***p* < 0.05**	9.20	*	*	1.00
	Max knee ext. rot. moment (Nm/kg)	-0.02	0.01	-0.03	0.04	-0.02	0.01	*p* = 0.20	1.74	-	-	-
	Max knee int. rot. moment (Nm/kg)	0.06	0.01	0.05	0.03	0.17	0.04	*p* = 0.28	1.24	-	-	-
Nine months post-surgery	Max knee ext. moment (Nm/kg)	-0.38	0.12	-0.34	0.10	-0.39	0.05	***p* < 0.05**	11.0	1.00	0.75	1.00
	Max knee flx. moment (Nm/kg)	0.75	0.40	0.73	0.25	0.96	0.30	***p* < 0.05**	8.26	0.67	0.59	1.00
	Knee flx at max ext. moment (°)	17.7	6.41	17.2	3.60	11.0	3.89	***p* < 0.05**	7.80	*	0.08	1.00
	Knee flx at max flx. moment (°)	27.9	9.50	22.2	4.95	25.5	5.57	*p* = 0.61	0.40	-	-	-
	Max knee ab. moment (Nm/kg)	-0.10	0.04	-0.13	0.07	-0.11	0.04	*p* = 0.98	0.03	-	-	-
	Max knee add. moment (Nm/kg)	0.30	0.08	0.26	0.11	0.46	0.13	***p* < 0.05**	9.20	*	*	1.00
	Max knee ext. rot. moment (Nm/kg)	-0.02	0.01	-0.02	0.01	-0.02	0.01	*p* = 0.20	1.74	-	-	-
	Max knee int. rot. moment (Nm/kg)	0.08	0.02	0.07	0.04	0.17	0.04	*p* = 0.28	1.24	-	-	-

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'

Table 43 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of kinetic variables in fixed bearing (FB) and mobile bearing (MB) patients

Level walking		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Max knee ext. moment (Nm/kg)	***p* < 0.05**	6.11	0.35	*	0.10
	Max knee flx. moment (Nm/kg)	*p* = 0.13	2.14	-	-	-
	Knee flx at max ext. moment (°)	***p* < 0.05**	4.21	0.36	0.56	0.77
	Knee flx at max flx. moment (°)	*p* = 0.48	0.62	-	-	-
	Max knee ab. moment (Nm/kg)	*p* = 0.60	0.35	-	-	-
	Max knee add. moment (Nm/kg)	***p* < 0.05**	17.7	*	0.08	*
	Max knee ext. rot. moment (Nm/kg)	*p* = 0.07	3.44	-	-	-
	Max knee int. rot. moment (Nm/kg)	***p* < 0.05**	16.3	*	*	*
MB	Max knee ext. moment (Nm/kg)	***p* < 0.05**	6.11	1.00	0.32	0.32
	Max knee flx. moment (Nm/kg)	*p* = 0.13	2.14	-	-	-
	Knee flx at max ext. moment (°)	***p* < 0.05**	4.21	0.11	*	1.00
	Knee flx at max flx. moment (°)	*p* = 0.48	0.62	-	-	-
	Max knee ab. moment (Nm/kg)	*p* = 0.60	0.35	-	-	-
	Max knee add. moment (Nm/kg)	***p* < 0.05**	17.7	*	1.00	*
	Max knee ext. rot. moment (Nm/kg)	*p* = 0.07	3.44	-	-	-
	Max knee int. rot. moment (Nm/kg)	***p* < 0.05**	16.3	*	0.07	*

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; '*' to 'Significant at the 0.05 level'

At pre-surgery, the MB group walked with a reduced maximum knee extension moment ($F_{1.31,23.49}$ = 11.0; p<0.05) than controls (Table 42). This finding was replicated in the maximum knee flexion moment ($F_{2,36}$ = 8.26; p<0.05), with a reduction observed when compared to controls. No differences were observed between FB and MB prostheses. The FB group at three months post-surgery walked with a reduced maximum knee extension moment ($F_{1.31,23.49}$ = 11.0; p<0.05), a greater knee flexion angle at the incidence of the maximum knee extension moment ($F_{1.51,27.24}$ = 7.80; p<0.05), and a reduced maximum knee adduction moment ($F_{1.3,23.48}$ = 9.20; p<0.05) than controls. Similar findings were evident in the MB group, with the patients walking with a reduced maximum knee extension moment ($F_{1.31,23.49}$ = 11.0; p<0.05), a greater knee flexion angle at the incidence of the maximum knee extension moment ($F_{1.31,23.49}$ = 11.0; p<0.05), and a reduced maximum knee adduction moment ($F_{1.3,23.48}$ = 9.20; p<0.05) when compared to controls. No differences were observed between FB and MB prostheses. At nine months post-surgery, the FB group walked with a greater knee flexion angle at the incidence of the maximum knee extension moment ($F_{1.51,27.24}$ = 7.80; p<0.05), in addition to a reduced maximum knee adduction moment ($F_{1.3,23.48}$ = 9.20; p<0.05) compared to controls. Significance was also reached in the MB group, with the patients walking with a reduced maximum knee adduction moment ($F_{1.3,23.48} = 9.20$; $p<0.05$) than controls. No differences were observed between FB and MB groups.

In the within-group between time point analysis (Table 43), reductions in the maximum knee adduction moment ($F_{2,36} = 17.7$; $p<0.05$) and maximum knee internal rotation moment ($F_{1.14,20.5} = 16.3$; $p<0.05$) were apparent in the FB group from pre-surgery to three months post-surgery. From three months post-surgery to nine months post-surgery, the FB group exhibited increases in the maximum knee extension moment ($F_{2,36} = 6.11$; $p<0.05$) and maximum knee internal rotation moment ($F_{1.14,20.5} = 16.3$; $p<0.05$). Reductions were also found in the maximum knee adduction moment ($F_{2,36} = 17.7$; $p<0.05$) and maximum knee internal rotation moment ($F_{1.14,20.5} = 16.3$; $p<0.05$) from pre-surgery to nine months post-surgery in the FB group. In the MB group, reductions were apparent in the maximum knee adduction moment ($F_{1.14,20.5} = 16.3$; $p<0.05$) and maximum knee internal rotation moment ($F_{1.14,20.5} = 16.3$; $p<0.05$) from pre-surgery to three months post-surgery. A reduction was also apparent in the knee flexion angle at the incidence of the maximum knee extension moment ($F_{1.3,23.42} = 4.21$; $p<0.05$) from three months post-surgery to nine months post-surgery. From pre-surgery to nine months post-surgery, there was a reduction in the maximum knee adduction moment ($F_{2,36} = 17.7$; $p<0.05$) and maximum knee internal rotational moment ($F_{1.14,20.5} = 16.3$; $p<0.05$) in the MB group.

5.4 Discussion

The FB and MB groups could not be distinguished following an adequate period of rehabilitation at nine months post-surgery [9, 99-101]. The most important finding of the current study was that there was no difference in the sagittal plane knee kinematics of the MB group when compared the FB group. Differences have been previously reported between FB and MB prostheses in kinematic variables during walking [78, 80] that provide support for the hypothetical, but largely unsubstantiated, biomechanical advantages of MB implantation [14]. There were also no differences greater than the MDC values for both within-session and between-session reliability detailed in Chapter 4 between FB and MB groups.

In the normal knee, axial rotation is permitted with the lateral femoral condyle contacting anterior to the midline of the tibia in extension [226]. With progressive flexion, the lateral femoral condyle translates proportionally to a position that is posterior to the midline of the tibia. The proposed increase of sagittal knee ROM in MB knees is achieved through this femoral rollback during knee flexion and subsequent internal rotation of the tibia during knee extension [227], similar to the normal knee. Mockel et al. [78] found these mechanical advantages elicited a greater mean stance phase knee flexion in MB prostheses when compared to FBs. Further, Kramers de-Quervain et al.[80] detailed an increase in the maximum knee flexion of MB prostheses when compared to FBs. Unfortunately, no pre-operative data were presented for Kramers de-Quervain et al. [80], making it difficult to conclude whether the post-surgery differences were representative of a true effect, or whether differences were apparent prior to implantation.

Despite advantageous findings for MB prostheses [78, 80], Sosio et al.[77] found no differences in knee flexion at heel contact, maximum knee flexion in stance, maximum knee extension in stance, and maximum knee flexion in swing between FB and MB groups during walking. Tibesku et al. [10] also found little mean differences in maximum knee flexion and ROM in stance and swing phases of gait during walking, not exceeding that of 0.5 of a standard deviation (SD) between-groups, although the authors did not statistically compare FB and MB groups but rather analysed the progression from pre-surgery to post-surgery.

In contrast to the mechanical advantages of MB implantation, Tibesku et al. [10] found an increase in maximum knee flexion from pre-surgery to post-surgery in the FB group, but not in the MB group in the within-group analyses. Both FB and MB groups in the current study walked with greater maximum knee flexion from pre-surgery to nine months post-surgery ($p<0.05$), with this difference also greater than the MDC values, and therefore inferring no differences between groups. Interestingly, the FB group also walked with greater ($p<0.05$; >MDC) sagittal knee ROM at nine months post-surgery than pre-surgery. Despite no significant differences in the MB group ($p>0.05$), a difference greater than the MDC values was also found in sagittal knee ROM at nine months post-surgery compared to pre-surgery, thus inferring no differences between FB and MB groups in this instance..

A difference between prostheses was observed at pre-surgery, with the MB group found to walk with reduced ($p<0.05$; >MDC) frontal plane knee ROM compared to the FB group, with both groups otherwise similar. Despite this finding, between-group similarity was compounded by the pre-surgery OKS, with no differences between-groups (Table 36), and both groups indicative of 'moderate to severe osteoarthritis' (31-40) [225]. This difference in frontal plane ROM was not apparent after surgery, however, suggesting there was little meaningful difference following a period of adequate rehabilitation.

In support of the axial mobility of the MB design, an increase ($p<0.05$; >MDC) in axial knee rotation in the MB group from pre-surgery to three and nine months post-surgery was determined. Despite this axial plane kinematic improvement, no ROM benefits were found in the sagittal plane. A potential reason for this is the relative ease of walking compared to other activities of daily living (ADLs) [183, 184, 228]. As walking requires less knee flexion than other activities [184], this proportionally corresponds to a reduced demand for axial rotation [15]. A similar increase in axial ROM was found in the FB group from pre-surgery to nine months post-surgery that almost reached significance ($p=0.05$), but was greater than the MDC values. This suggests that the FB prostheses exhibit enough residual axial rotation between the femoral component and the polyethylene insert to perform adequately during walking. Activities that require greater ROM at the knee are therefore necessary to further investigate the effect of MB implantation compared to FB designs.

Although no differences were found between FB and MB groups, refuting the preliminary observations of Mockel et al. [78] and Kramers-de Quervain et al. [80], important differences were highlighted between FB and MB groups compared to controls. Both FB and MB groups walked with a greater ($p<0.05$; >MDC) minimum knee flexion than controls following surgery, suggesting greater potential quadriceps activation in order to stabilise the knee in the absence of optimised anterior stability due to the excision of the anterior cruciate ligament (ACL) [29], in addition to the presence of a slight flexion contracture [229]. This suggestion was supported by the continuous waveforms of the sagittal knee kinematics, depicting an increased flexion trend around the mid-stance phase of the gait cycle (24%-44%) at three months post-surgery that was outside of the 95% confidence intervals in the FB and MB groups compared to controls. This trend was also evident at nine months post-surgery, although not to the magnitude observed at three months post-surgery, suggesting improved stability at a period following adequate rehabilitation.

The post-surgery gait patterns observed were in contrast to findings at pre-surgery, with a reduction ($p<0.05$) in the maximum knee flexion moment (Table 42) during the loading response phase of the gait cycle (0%-20%) in FB and MB groups compared to controls at pre-surgery, although this difference was less than the MDC values. It has been postulated that mechanisms to reduce loading are adopted to reduce shear forces at the knee, or attributed to pain avoidance patterns developed pre-surgery [230]. Reduced magnitudes of knee flexion moments can often be explained by reductions in knee flexion (i.e. increased knee extension), a trend observed outside of the 95% confidence intervals in the FB and MB groups at pre-surgery in the current study (Figure 11). Maintaining a more extended knee reduces the eccentric load on the quadriceps and is therefore an integral component of the quadriceps avoidance strategy. In contrast to other reports [102, 117], the TKR patients did not display a typical quadriceps avoidance strategy following surgery. Smith et al. [117] has indicated that pre-surgery gait patterns can be retained up to 18 months post-surgery, even without the presence of pain.

Reductions ($p<0.05$) were found in both FB and MB groups in the maximum knee adduction moment when compared to controls following surgery, although this difference was less than the MDC values. It has been previously found that from a mechanical perspective, reduced knee adduction moments suggest reduced loading at the medial compartment of the knee [29]. This is a common finding in the literature [84, 91, 93, 111], and the results from this study further suggest that this difference is independent of prosthesis design, as no differences ($p<0.05$; >MDC) were found between FB and MB groups. Benedetti et al. [111] found related co-contraction of the biceps femoris and tibialis anterior on the affected side in patients following TKR, suggesting an attempt at controlling knee kinematics [231]. This co-contraction, coupled with a reduced maximum adduction moment could suggest instability in the replaced knee. Further, these reductions in ipsilateral knee loading may invoke greater loading in the contralateral knee, with an unequal loading ratio being an important risk factor for OA progression [232].

Fixed bearing and MB groups also walked slower (*p*<0.05) than controls at pre-surgery and post-surgery time points, although only the FB group exhibited differences greater than the MDC values. The FB group walked with a reduced (*p*<0.05) stride length and increased stride time at post-surgery compared to controls, although stride time was less than the MDC values. Significance was not reached in the MB group for stride length or stride time, although stride length exhibited differences greater than the MDC. A reduced stride length in the FB group may indicate a more conscious effort to minimise pain whilst also reducing the kinetic demands on the affected side compared to controls [233]. It is difficult to deduce a specific cause for reduced stride length as this is likely to be multi-factorial. A reduced stride length could also be a product of walking with a reduced gait velocity, thus inferring no direct functional discrepancies. These altered walking patterns demonstrated by the FB and MB groups could not be attributed to poor clinical outcomes achieved by this cohort. The patients in this study achieved clinical outcomes comparable to the best reported outcomes after TKR using FB and MB prostheses [234].

5.4.1 Limitations

The predominant limitation of the current study is that of a small sample size, although comparable to previous literature comparing FB and MB groups by means of gait analysis [29, 77, 79, 80]. A power calculation was undertaken at the investigation outset, which suggested a total sample size of 21, inclusive of the FB, MB, and control groups, with the study including 24. We are therefore confident that the results are of sufficient statistical power to distinguish a ‘medium’ effect among groups [113]. This suggests that when coupled with the relative biomechanical ease of walking, this study may not have adequate power to distinguish ‘small’ effects between-groups.

A limitation which could have potentially confounded the comparisons between the TKR groups and controls is that the patients were typically heavier and had a higher

BMI than the control group. In the kinetic variables where mass has a direct impact on the magnitude of the ground reaction forces, normalisation of the joint moments to body mass was undertaken in an attempt to control for these differences. Despite this, no compensatory strategies were apparent for controlling potential kinematic differences between obese and non-obese populations. This could have contributed to the findings of reduced ROM in the patient groups compared to controls.

In addition, as discussed in Chapter 4, a self-selected gait velocity was chosen for experimentation in this thesis, with the patient groups found to walk with a reduced gait velocity compared to the controls at all time points. This could have also contributed to the findings of reduced ROM in the patient groups compared to controls, in addition to the reduction of other spatiotemporal variables. Most importantly, however, due to the gait velocity being similar between FB and MB patients at all time points ($p>0.05$), this is unlikely to have any considerable effect on the interpretation of biomechanical differences between FB and MB groups, which was the overarching aim of this study.

5.5 Conclusions

- There were no differences found between FB and MB prostheses that were not be attributed to differences at pre-surgery, thus suggesting MB prostheses do not offer biomechanical advantages over FB designs during walking.
- More biomechanically demanding activities are required to further investigate whether MB total knee prostheses offer biomechanical advantages over FB designs.
- Both FB and MB groups showed characteristics of increased stance phase knee flexion when compared to age and gender matched controls following TKR surgery, suggesting increased quadriceps activation in order to stabilise the knee. This could, however, be due to body mass, BMI, and gait velocity differences between the patient and control groups.

6.0 Biomechanical analysis of fixed bearing and mobile bearing total knee replacement patients during stair negotiation, sit to stand, and stand to sit

6.1 Introduction

No biomechanical advantages of implantation with mobile bearing (MB) total knee prostheses were established during walking (Chapter 5). Due to differences in activity difficulty, assessing patients over multiple functional activities is a more valid method of quantifying the function of patients with osteoarthritis (OA) and following total knee replacement (TKR) surgery than walking alone [234]. It is accepted that stair ascent and stair descent are more biomechanically demanding activities than walking due to increased muscular demands [185, 235] over a greater range of movement (ROM) [183, 228]. As such, it has been suggested that these activities are more likely to highlight differences that may go undetected during walking [236].

In addition to the outlined theoretical biomechanical advantages of MB designs [14], the results of the literature review in Chapter 2 also highlighted the presence of compensatory mechanisms due to instability in MB designs when compared to fixed bearings (FBs) [29, 79]. These limited findings warrant further investigation as replication of these results could have considerable implications for the use of MBs. In order to further assess potential instability, sit to stand and stand to sit activities were also utilised with the calculation of the loading ratio.

The primary aim of this chapter was to analyse whether MBs offered biomechanical advantages during stair negotiation. The previous findings of disadvantageous compensatory mechanisms due to instability in MBs were also assessed during stair negotiation, sit to stand, and stand to sit activities. This study has, in part, been published in the Bone and Joint Journal (Appendix B).

6.2 Method

6.2.1 A priori power calculation

The power calculation at the study outset was described in Chapter 5 (‘5.2.1 A priori power calculation’).

6.2.2 Participants

The patient cohort that was described in Chapter 4 (‘4.2.1 Participants’) was used in this study, in addition to the age and gender matched controls.

6.2.3 Instrumentation set-up and protocol

Gait analyses were undertaken in the FB and MB groups at pre-surgery, three months post-surgery, and nine months post-surgery, in addition to a single testing session for the age and gender matched controls as described in Chapter 4 (‘4.2.1 Participants’). Stair ascent, stair descent, sit to stand, and stand to sit activities were undertaken as described in Chapter 3 (‘3.2.1 Activities of daily living protocol used in the three dimensional motion analysis system’).

The 12 camera three dimensional motion analysis system (MX, Vicon, Oxford, UK), instrumented stair rig (Physio-Med Services LTD, Glossop, UK), and integrated force plates (MC818 and OR6-7, AMTI, Watertown MA, USA) were calibrated and set-up using the methods detailed in Chapter 3 (‘3.2 Three dimensional motion analysis system’).

6.2.4 Data analysis

All data cleaning and processing in the three dimensional motion analysis system, instrumented stair rig, and integrated force plates was undertaken in line with the methods described in Chapter 3 (‘3.2.2 Data cleaning and processing in the three dimensional motion analysis system’). All statistical analyses were undertaken in line with the methods described in Chapter 5 (‘5.2.4 Data analysis’).

6.3 Results

As some patients struggled to adequately perform the activities, ≥5 of the 8 participants in each group (FB, MB, and control) were required to adequately perform each activity in order for the group to be included in analysis. This was observed to provide a level of credence to the subsequent data interpretation.

6.3.1. Spatiotemporal

6.3.1.1 Stair ascent

Pairwise comparisons are presented in Table 44 relating to the differences between FB, MB, and control groups in spatiotemporal variables during stair ascent at pre-surgery, three months post-surgery, and nine months post-surgery. Table 45 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the spatiotemporal variables during stair ascent.

Table 44 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of spatiotemporal variables at pre-surgery, three months post-surgery, and nine months post-surgery time points during stair ascent

Stair ascent		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Cadence (steps/min)	63.7	24.3	54.7	2.38	96.4	18.9	$p < 0.05$	10.3	*	N/A	N/A
	Foot off (gait cycle %)	64.9	5.72	64.3	0.45	61.4	2.81	$p = 0.12$	2.39	-	N/A	N/A
	Stride length (m)	0.70	0.05	0.74	0.02	0.76	0.05	$p < 0.05$	12.2	0.12	N/A	N/A
	Stride time (s)	2.12	0.77	2.20	0.09	1.28	0.23	$p < 0.05$	11.3	*	N/A	N/A
	Gait velocity (m/s)	0.38	0.16	0.34	0.02	0.61	0.12	$p < 0.05$	18.1	*	N/A	N/A
Three months post-surgery	Cadence (steps/min)	83.2	21.3	72.1	10.8	96.4	18.9	$p < 0.05$	10.3	0.76	N/A	N/A
	Foot off (gait cycle %)	60.1	3.08	63.2	1.20	61.4	2.81	$p = 0.12$	2.39	-	N/A	N/A
	Stride length (m)	0.69	0.02	0.70	0.04	0.76	0.05	$p < 0.05$	12.2	*	N/A	N/A
	Stride time (s)	1.56	0.41	1.70	0.28	1.28	0.23	$p < 0.05$	11.3	0.45	N/A	N/A
	Gait velocity (m/s)	0.45	0.11	0.42	0.08	0.61	0.12	$p < 0.05$	18.1	0.08	N/A	N/A
Nine months post-surgery	Cadence (steps/min)	79.2	13.6	70.5	8.21	96.4	18.9	$p < 0.05$	10.3	0.27	0.11	1.00
	Foot off (gait cycle %)	62.8	4.20	63.3	1.14	61.4	2.81	$p = 0.12$	2.39	-	-	-
	Stride length (m)	0.67	0.02	0.72	0.06	0.76	0.05	$p < 0.05$	12.2	*	0.61	0.29
	Stride time (s)	1.56	0.31	1.72	0.20	1.28	0.23	$p < 0.05$	11.3	0.26	0.08	1.00
	Gait velocity (m/s)	0.44	0.07	0.42	0.05	0.61	0.12	$p < 0.05$	18.1	*	*	1.00

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Table 45 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of spatiotemporal variables in fixed bearing (FB) and mobile bearing (MB) patients during stair ascent

Stair ascent		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Cadence (steps/min)	*p* = 0.09	2.72	-	-	-
	Foot off (gait cycle %)	*p* = 0.11	2.92	-	-	-
	Stride length (m)	*p* = 0.24	1.53	-	-	-
	Stride time (s)	*p* = 0.06	3.66	-	-	-
	Gait velocity (m/s)	*p* = 0.26	1.43	-	-	-
MB	Cadence (steps/min)	*p* = 0.09	2.72	N/A	N/A	N/A
	Foot off (gait cycle %)	*p* = 0.11	2.92	N/A	N/A	N/A
	Stride length (m)	*p* = 0.24	1.53	N/A	N/A	N/A
	Stride time (s)	*p* = 0.06	3.66	N/A	N/A	N/A
	Gait velocity (m/s)	*p* = 0.26	1.43	N/A	N/A	N/A

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Reductions were observed in FB patients compared to controls in cadence ($F_{2,20}$ = 10.3; p<0.05) and gait velocity ($F_{2,20}$ = 18.1; p<0.05), with an increase in stride time ($F_{2,20}$ = 11.3; p<0.05) during stair ascent at pre-surgery (Table 44). An insufficient number of MB patients were able to adequately perform the stair ascent activity at pre-surgery (*n*=3) and three months post-surgery (*n*=4), therefore no analysis was undertaken. The FB group stair ascended with reduced stride length ($F_{1.31,13.11}$ = 12.2; p<0.05) compared to controls at three months post-surgery. At nine months post-surgery, the FB group stair ascended with a reduced stride length ($F_{1.31,13.11}$ = 12.2; p<0.05) and gait velocity ($F_{2,20}$ = 18.1; p<0.05) than controls. The MB group also displayed a reduction in gait velocity ($F_{2,20}$ = 18.1; p<0.05) compared to controls. No differences were observed between FB and MB prostheses at nine months post-surgery. No conditions reached significance in the within-group between time point analysis (Table 45).

6.3.1.2 Stair descent

Pairwise comparisons are presented in Table 46 relating to the differences between FB, MB, and control groups in spatiotemporal variables during stair descent at pre-surgery, three months post-surgery, and nine months post-surgery. Table 47 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the spatiotemporal variables during stair descent.

Table 46 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of spatiotemporal variables at pre-surgery, three months post-surgery, and nine months post-surgery time points in stair descent

Stair descent		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Cadence (steps/min)	64.0	19.2	33.8	12.3	100	14.3	$\boldsymbol{p < 0.05}$	19.2	*	N/A	N/A
	Foot off (gait cycle %)	66.2	6.59	77.1	4.77	63.4	1.93	$\boldsymbol{p < 0.05}$	26.3	0.84	N/A	N/A
	Stride length (m)	0.68	0.05	0.70	0.03	0.74	0.04	$p = 0.16$	2.05	-	N/A	N/A
	Stride time (s)	2.01	0.50	3.85	1.36	1.23	0.20	$\boldsymbol{p < 0.05}$	12.1	0.06	N/A	N/A
	Gait velocity (m/s)	0.37	0.12	0.20	0.08	0.62	0.08	$\boldsymbol{p < 0.05}$	16.4	*	N/A	N/A
Three months post-surgery	Cadence (steps/min)	81.3	32.4	43.1	1.91	100	14.3	$\boldsymbol{p < 0.05}$	19.2	0.44	*	0.17
	Foot off (gait cycle %)	65.8	3.48	75.5	6.19	63.4	1.93	$\boldsymbol{p < 0.05}$	26.3	0.61	*	*
	Stride length (m)	0.72	0.04	0.67	0.04	0.74	0.04	$p = 0.16$	2.05	-	-	-
	Stride time (s)	1.79	1.03	2.80	0.13	1.23	0.20	$\boldsymbol{p < 0.05}$	12.1	0.40	*	0.22
	Gait velocity (m/s)	0.49	0.21	0.24	0.00	0.62	0.08	$\boldsymbol{p < 0.05}$	16.4	0.34	*	0.15
Nine months post-surgery	Cadence (steps/min)	76.3	40.5	71.5	4.21	100	14.3	$\boldsymbol{p < 0.05}$	19.2	0.38	0.55	1.00
	Foot off (gait cycle %)	67.1	3.84	70.9	3.36	63.4	1.93	$\boldsymbol{p < 0.05}$	26.3	0.13	*	0.40
	Stride length (m)	0.72	0.06	0.68	0.03	0.74	0.04	$p = 0.16$	2.05	-	-	-
	Stride time (s)	2.08	1.30	1.69	0.10	1.23	0.20	$\boldsymbol{p < 0.05}$	12.1	0.23	1.00	1.00
	Gait velocity (m/s)	0.47	0.28	0.40	0.04	0.62	0.08	$\boldsymbol{p < 0.05}$	16.4	0.49	0.43	1.00

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Table 47 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of spatiotemporal variables in fixed bearing (FB) and mobile bearing (MB) patients during stair descent

Stair descent		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Cadence (steps/min)	$p = 0.07$	2.96	-	-	-
	Foot off (gait cycle %)	$p = 0.48$	0.77	-	-	-
	Stride length (m)	$p = 0.87$	0.14	-	-	-
	Stride time (s)	$\boldsymbol{p < 0.05}$	3.68	1.00	1.00	1.00
	Gait velocity (m/s)	$p = 0.11$	2.41	-	-	-
MB	Cadence (steps/min)	$p = 0.07$	2.96	N/A	-	N/A
	Foot off (gait cycle %)	$p = 0.48$	0.77	N/A	-	N/A
	Stride length (m)	$p = 0.87$	0.14	N/A	-	N/A
	Stride time (s)	$\boldsymbol{p < 0.05}$	3.68	N/A	0.33	N/A
	Gait velocity (m/s)	$p = 0.11$	2.41	N/A	-	N/A

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. < 5 of 8 participants in each group)'

Reductions were found in the FB group when compared to the control group in cadence ($F_{2,18} = 19.2$; $p<0.05$) and gait velocity ($F_{2,18} = 16.4$; $p<0.05$) during stair descent at pre-surgery (Table 46). An insufficient number of patients in the MB group were able to adequately perform the stair descent activity at pre-surgery (n=2), with the group excluded from analysis. At three months post-surgery, no differences between the FB and control groups were observed. The MB group stair descended with reduced cadence ($F_{2,18} = 19.2$; $p<0.05$) and gait velocity ($F_{2,18} = 16.4$; $p<0.05$), as well as an increased foot off percentage ($F_{2,18} = 26.3$; $p<0.05$) and stride time ($F_{2,18} = 12.1$; $p<0.05$) than controls at three months post-surgery. The MB group also stair descended with an increased foot off percentage ($F_{2,18} = 26.3$; $p<0.05$) compared to the FB group at three months post-surgery (FB=66.8 ±3.48gait cycle%; MB=75.5 ±6.19gait cycle%). At nine months post-surgery, the MB group stair descended with a greater foot off percentage ($F_{2,18} = 26.3$; $p<0.05$) compared to the controls, with no differences between FB and MB groups. Only stride time reached significance ($F_{2,18} = 12.1$; $p<0.05$) in the within-group between time point analysis in Table 47, although no differences were observed in the pairwise comparisons.

6.3.2 Knee kinematic

6.3.2.1 Stair ascent

Continuous waveforms of the sagittal knee kinematics are presented in Figure 12 for the FB, MB, and control groups at three months post-surgery and nine months post-surgery. Only three and nine month post-surgery waveforms are presented as fewer patients were able to adequately perform the activity at pre-surgery, thus displaying greater variability when depicted graphically. Pairwise comparisons are presented in Table 48 relating to the differences between FB, MB, and control groups in kinematic variables during stair ascent at pre-surgery, three months post-surgery, and nine months post-surgery. Table 49 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the kinematic variables during stair ascent.

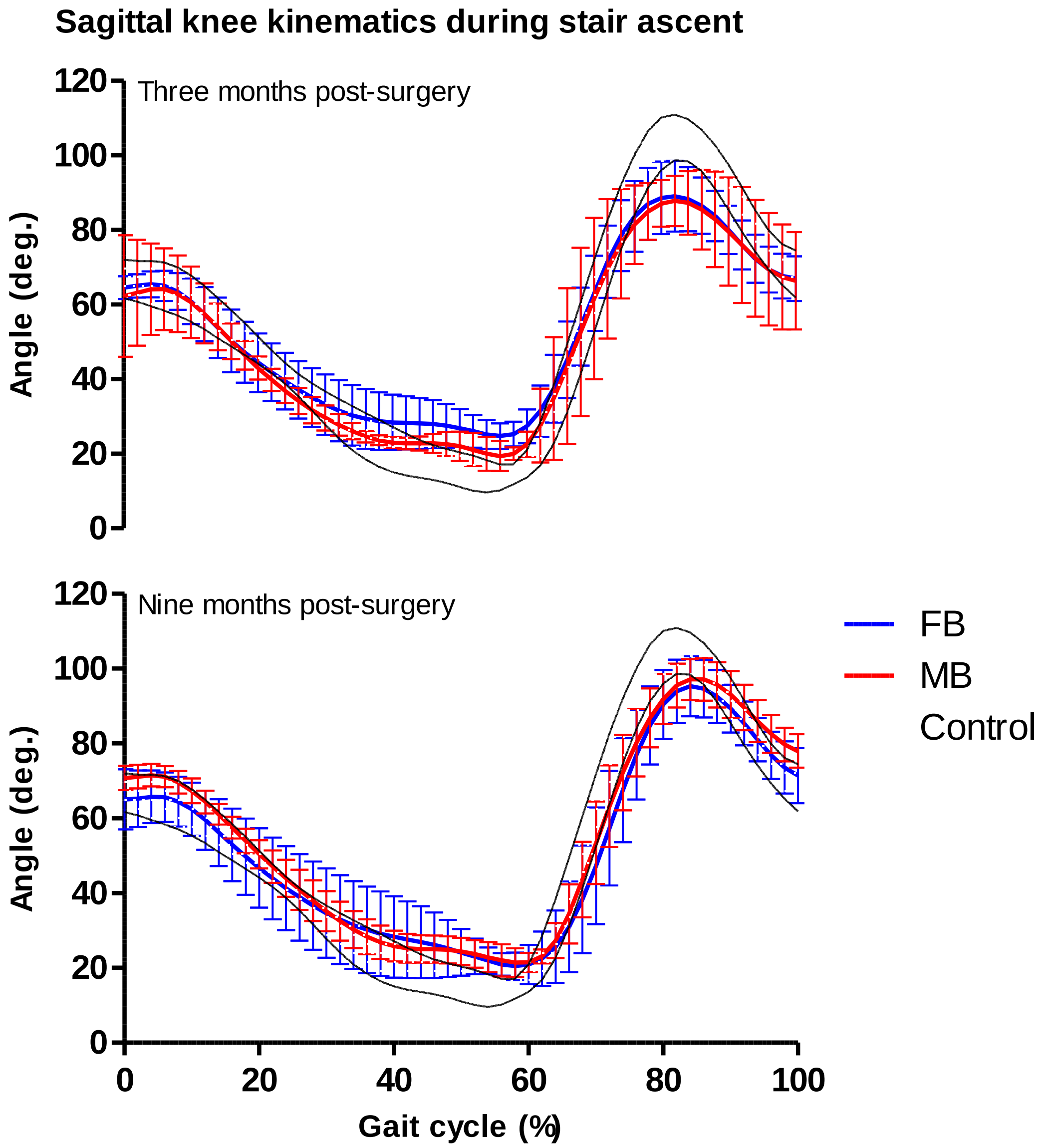

Figure 12 – Gait cycle percentage normalised continuous waveforms of the sagittal knee kinematics for the fixed bearing, mobile bearing, and control groups at three months post-surgery and nine months post-surgery. Error bars represent 95% confidence intervals. The white area between the black lines represents the 95% confidence interval range for the control group

Table 48 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of kinematic variables at pre-surgery, three months post-surgery, and nine months post-surgery time points in stair ascent

Stair ascent		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Min knee flexion (°)	19.9	8.72	13.4	4.17	11.6	2.60	***p*< 0.05**	6.52	0.08	N/A	N/A
	Max knee flexion (°)	102	1.94	85.7	16.5	106	7.36	***p*< 0.05**	10.6	1.00	N/A	N/A
	Sagittal knee ROM (°)	83.8	6.88	71.4	14.8	94.0	7.59	***p*< 0.05**	32.2	0.23	N/A	N/A
	Max knee abduction (°)	-11.4	16.7	1.01	9.21	-12.6	10.1	*p* = 0.73	0.32	-	N/A	N/A
	Max knee adduction (°)	9.80	16.2	19.0	5.27	8.14	7.30	*p* = 0.92	0.03	-	N/A	N/A
	Frontal knee ROM (°)	21.2	2.27	18.0	7.24	20.7	7.12	*p* = 0.31	1.25	-	N/A	N/A
	Max knee external rotation (°)	-5.83	5.01	-11.0	6.45	-9.86	15.6	*p* = 0.19	1.79	-	N/A	N/A
	Max knee internal rotation (°)	13.5	10.5	7.78	5.11	9.49	15.6	*p* = 0.06	3.28	-	N/A	N/A
	Axial knee ROM (°)	19.3	5.59	19.7	4.27	19.4	6.57	*p* = 0.29	1.32	-	N/A	N/A
Three months post-surgery	Min knee flexion (°)	21.9	4.71	18.1	1.09	11.6	2.60	***p*< 0.05**	6.52	*	N/A	N/A
	Max knee flexion (°)	89.0	11.1	88.6	6.38	106	7.36	***p*< 0.05**	10.6	*	N/A	N/A
	Sagittal knee ROM (°)	65.9	6.62	70.6	7.41	94.0	7.59	***p*< 0.05**	32.2	*	N/A	N/A
	Max knee abduction (°)	-19.7	10.5	-16.6	1.72	-12.6	10.1	*p* = 0.73	0.32	-	N/A	N/A
	Max knee adduction (°)	-0.20	22.3	1.09	6.01	8.14	7.30	*p* = 0.92	0.03	-	N/A	N/A
	Frontal knee ROM (°)	19.53	12.4	17.7	5.74	20.7	7.12	*p* = 0.31	1.25	-	N/A	N/A
	Max knee external rotation (°)	-8.03	12.9	-3.47	2.12	-9.86	15.6	*p* = 0.19	1.79	-	N/A	N/A
	Max knee internal rotation (°)	7.77	11.3	8.10	2.94	9.49	15.6	*p* = 0.06	3.28	-	N/A	N/A
	Axial knee ROM (°)	15.8	4.31	11.6	2.31	19.4	6.57	*p* = 0.29	1.32	-	N/A	N/A
Nine months post-surgery	Min knee flexion (°)	16.9	7.28	20.3	2.87	11.6	2.60	***p*< 0.05**	6.52	0.24	*	1.00
	Max knee flexion (°)	94.1	9.10	93.0	4.57	106	7.36	***p*< 0.05**	10.6	0.07	0.10	1.00
	Sagittal knee ROM (°)	76.1	9.95	72.7	5.31	94.0	7.59	***p*< 0.05**	32.2	*	*	1.00
	Max knee abduction (°)	-20.9	15.4	-5.46	4.34	-12.6	10.1	*p* = 0.73	0.32	-	-	-
	Max knee adduction (°)	2.06	20.6	8.42	6.79	8.14	7.30	*p* = 0.92	0.03	-	-	-
	Frontal knee ROM (°)	22.9	8.43	13.9	7.74	20.7	7.12	*p* = 0.31	1.25	-	-	-
	Max knee external rotation (°)	-0.02	13.0	-11.0	6.90	-9.86	15.6	*p* = 0.19	1.79	-	-	-
	Max knee internal rotation (°)	19.1	12.3	3.14	5.15	9.49	15.6	*p* = 0.06	3.28	-	-	-
	Axial knee ROM (°)	19.1	6.22	14.1	1.97	19.4	6.57	*p* = 0.29	1.32	-	-	-

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Table 49 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of kinematic variables in fixed bearing (FB) and mobile bearing (MB) patients during stair ascent

Stair ascent		Time point		Pe-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Min knee flexion (°)	$p = 0.49$	0.61	-	-	-
	Max knee flexion (°)	$p = 0.27$	1.38	-	-	-
	Sagittal knee ROM (°)	$\boldsymbol{p < 0.05}$	6.38	*	*	0.14
	Max knee abduction (°)	$p = 0.06$	4.11	-	-	-
	Max knee adduction (°)	$p = 0.11$	2.86	-	-	-
	Frontal knee ROM (°)	$p = 0.92$	0.08	-	-	-
	Max knee external rotation (°)	$p = 0.67$	0.41	-	-	-
	Max knee internal rotation (°)	$p = 0.63$	0.31	-	-	-
	Axial knee ROM (°)	$\boldsymbol{p < 0.05}$	3.53	0.55	0.13	1.00
MB	Min knee flexion (°)	$p = 0.49$	0.61	N/A	N/A	N/A
	Max knee flexion (°)	$p = 0.27$	1.38	N/A	N/A	N/A
	Sagittal knee ROM (°)	$\boldsymbol{p < 0.05}$	6.38	N/A	N/A	N/A
	Max knee abduction (°)	$p = 0.06$	4.11	N/A	N/A	N/A
	Max knee adduction (°)	$p = 0.11$	2.86	N/A	N/A	N/A
	Frontal knee ROM (°)	$p = 0.92$	0.08	N/A	N/A	N/A
	Max knee external rotation (°)	$p = 0.67$	0.41	N/A	N/A	N/A
	Max knee internal rotation (°)	$p = 0.63$	0.31	N/A	N/A	N/A
	Axial knee ROM (°)	$\boldsymbol{p < 0.05}$	3.53	N/A	N/A	N/A

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

No differences were observed outside of the 95% confidence intervals between FB and MB groups across the continuous waveforms for sagittal knee kinematics (Figure 12). Differences outside of the 95% confidence intervals were apparent at three and nine months post-surgery, with the FB and MB groups indicative of greater knee flexion during mid to terminal stance phase (50%-60%) than controls. In addition, the FB and MB groups displayed reduced knee flexion during mid-swing phase (80%) compared to controls, a difference outside of the 95% confidence intervals.

These findings were supported by the discrete variables, with the FB group stair ascending with greater minimum knee flexion ($F_{2,20} = 6.52$; $p<0.05$) and reduced maximum knee flexion ($F_{2,20} = 10.6$; $p<0.05$) than controls at three months post-surgery (Table 48). An overall reduction in sagittal knee ROM ($F_{2,20} = 32.2$; $p<0.05$) was also apparent in the FB group when compared to controls. An insufficient number of patients in the MB group were able to adequately perform the stair ascent activity at pre-surgery (n=3) and three months post-surgery (n=4), with the group excluded from analysis. The FB group at nine months post-surgery stair ascended with a reduced sagittal knee ROM ($F_{2,20}$ = 32.2; p<0.05) than controls. The MB group ambulated with a greater minimum knee flexion angle ($F_{2,20}$ = 6.52; p<0.05) and a reduced sagittal knee ROM ($F_{2,20}$ = 32.2; p<0.05) than controls. No differences between FB and MB groups were observed. In the within-group between time point analysis, the FB group exhibited a reduction in sagittal knee ROM ($F_{2,24}$ = 6.38; p<0.05) from pre-surgery to three months post-surgery in stair ascent (Table 48).

6.3.2.2 Stair descent

Continuous waveforms of the sagittal knee kinematics are presented in Figure 13 for the FB, MB, and control groups at three months post-surgery and nine months post-surgery. Only three and nine month post-surgery waveforms are presented as fewer patients were able to adequately perform the activity at pre-surgery, thus displaying greater variability when depicted graphically. Pairwise comparisons are presented in Table 50 relating to the differences between FB, MB, and control groups in kinematic variables during stair descent at pre-surgery, three months post-surgery, and nine months post-surgery. Table 51 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the kinematic variables during stair descent.

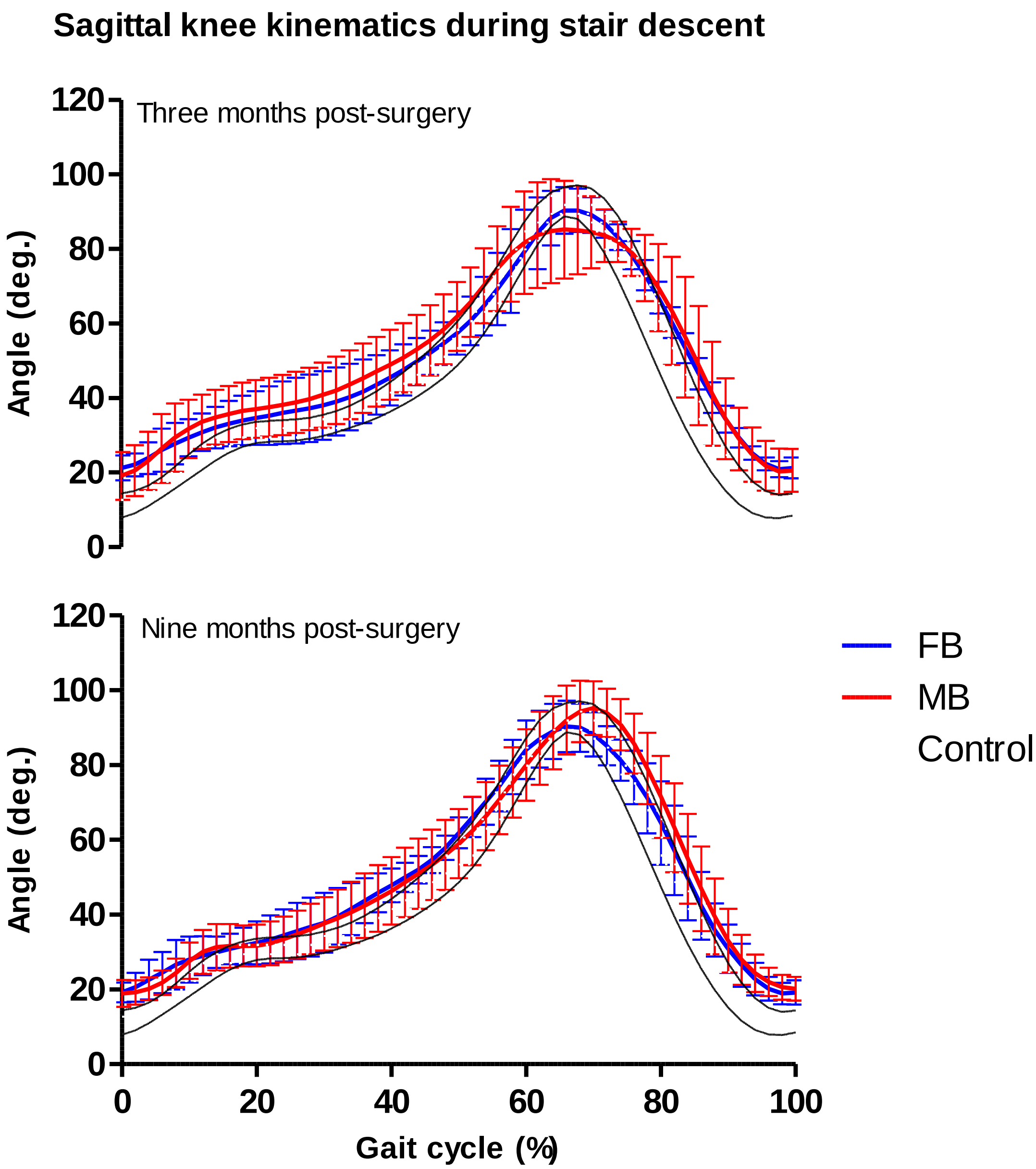

Figure 13 – Gait cycle percentage normalised continuous waveforms of the sagittal knee kinematics for the fixed bearing, mobile bearing, and control groups at three months post-surgery and nine months post-surgery. Error bars represent 95% confidence intervals. The white area between the black lines represents the 95% confidence interval range for the control group.

Table 50 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of kinematic variables at pre-surgery, three months post-surgery, and nine months post-surgery time points during stair descent

Stair descent		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Min knee flexion (°)	14.3	5.17	2.82	2.10	9.89	3.49	$\boldsymbol{p < 0.05}$	7.98	0.25	N/A	N/A
	Max knee flexion (°)	98.0	4.36	75.2	8.52	95.4	4.24	$\boldsymbol{p < 0.05}$	4.04	1.00	N/A	N/A
	Sagittal knee ROM (°)	83.8	1.91	72.4	10.6	85.5	4.83	$\boldsymbol{p < 0.05}$	4.11	1.00	N/A	N/A
	Max knee abduction (°)	-10.1	14.5	2.31	3.04	-9.58	10.0	$p = 0.36$	1.08	-	N/A	N/A
	Max knee adduction (°)	10.5	13.2	20.2	0.88	8.02	7.64	$p = 0.89$	0.05	-	N/A	N/A
	Frontal knee ROM (°)	18.3	6.14	17.9	2.16	17.6	6.35	$p = 0.13$	2.26	-	N/A	N/A
	Max knee external rotation (°)	-7.94	6.09	-17.4	1.63	-10.8	14.7	$\boldsymbol{p < 0.05}$	6.59	1.00	N/A	N/A
	Max knee internal rotation (°)	9.18	9.34	3.38	0.64	4.77	14.0	$\boldsymbol{p < 0.05}$	4.65	1.00	N/A	N/A
	Axial knee ROM (°)	17.1	7.00	20.8	2.27	15.6	3.40	$p = 0.13$	2.27	-	N/A	N/A
Three months post-surgery	Min knee flexion (°)	20.1	2.63	23.3	4.14	9.89	3.49	$\boldsymbol{p < 0.05}$	7.98	*	*	0.82
	Max knee flexion (°)	93.2	4.69	83.1	2.76	95.4	4.24	$\boldsymbol{p < 0.05}$	4.04	1.00	*	*
	Sagittal knee ROM (°)	73.1	4.10	59.8	6.89	85.5	4.83	$\boldsymbol{p < 0.05}$	4.11	*	*	*
	Max knee abduction (°)	-12.7	8.49	-10.4	3.50	-9.58	10.0	$p = 0.36$	1.08	-	-	-
	Max knee adduction (°)	7.75	13.5	0.54	3.55	8.02	7.64	$p = 0.89$	0.05	-	-	-
	Frontal knee ROM (°)	20.4	7.59	10.9	0.04	17.6	6.35	$p = 0.13$	2.26	-	-	-
	Max knee external rotation (°)	-11.0	7.17	-12.3	1.61	-10.8	14.7	$\boldsymbol{p < 0.05}$	6.59	1.00	1.00	1.00
	Max knee internal rotation (°)	7.04	10.1	-1.01	2.20	4.77	14.0	$\boldsymbol{p < 0.05}$	4.65	1.00	1.00	1.00
	Axial knee ROM (°)	18.0	5.18	11.3	0.60	15.6	3.40	$p = 0.13$	2.27	-	-	-
Nine months post-surgery	Min knee flexion (°)	18.0	2.98	18.3	3.64	9.89	3.49	$\boldsymbol{p < 0.05}$	7.98	*	*	1.00
	Max knee flexion (°)	93.1	7.78	92.6	8.27	95.4	4.24	$\boldsymbol{p < 0.05}$	4.04	1.00	1.00	1.00
	Sagittal knee ROM (°)	75.1	9.46	74.3	4.63	85.5	4.83	$\boldsymbol{p < 0.05}$	4.11	0.06	0.17	1.00
	Max knee abduction (°)	-14.2	13.1	-7.45	1.92	-9.58	10.0	$p = 0.36$	1.08	-	-	-
	Max knee adduction (°)	7.87	15.8	13.2	7.45	8.02	7.64	$p = 0.89$	0.05	-	-	-
	Frontal knee ROM (°)	22.1	5.34	20.6	5.52	17.6	6.35	$p = 0.13$	2.26	-	-	-
	Max knee external rotation (°)	-8.16	6.99	-15.4	7.78	-10.8	14.7	$\boldsymbol{p < 0.05}$	6.59	1.00	1.00	1.00
	Max knee internal rotation (°)	11.9	5.98	-0.87	9.63	4.77	14.0	$\boldsymbol{p < 0.05}$	4.65	0.90	1.00	0.63
	Axial knee ROM (°)	20.1	2.39	14.5	1.85	15.6	3.40	$p = 0.13$	2.27	-	-	-

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Table 51 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of kinematic variables in fixed bearing (FB) and mobile bearing (MB) patients during stair ascent

Stair descent		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Min knee flexion (°)	**$p < 0.05$**	46.1	*	0.43	*
	Max knee flexion (°)	$p = 0.06$	4.07	-	-	-
	Sagittal knee ROM (°)	**$p < 0.05$**	12.2	*	0.89	*
	Max knee abduction (°)	$p = 0.24$	1.51	-	-	-
	Max knee adduction (°)	$p = 0.16$	2.09	-	-	-
	Frontal knee ROM (°)	$p = 0.06$	3.90	-	-	-
	Max knee external rotation (°)	$p = 0.87$	0.15	-	-	-
	Max knee internal rotation (°)	$p = 0.58$	0.56	-	-	-
	Axial knee ROM (°)	$p = 0.19$	1.91	-	-	-
MB	Min knee flexion (°)	**$p < 0.05$**	46.1	N/A	0.12	N/A
	Max knee flexion (°)	$p = 0.06$	4.07	N/A	-	N/A
	Sagittal knee ROM (°)	**$p < 0.05$**	12.2	N/A	*	N/A
	Max knee abduction (°)	$p = 0.24$	1.51	N/A	-	N/A
	Max knee adduction (°)	$p = 0.16$	2.09	N/A	-	N/A
	Frontal knee ROM (°)	$p = 0.06$	3.90	N/A	-	N/A
	Max knee external rotation (°)	$p = 0.87$	0.15	N/A	-	N/A
	Max knee internal rotation (°)	$p = 0.58$	0.56	N/A	-	N/A
	Axial knee ROM (°)	$p = 0.19$	1.91	N/A	-	N/A

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

No differences were observed outside of the 95% confidence intervals between FB and MB groups across the continuous waveforms for sagittal knee kinematics (Figure 13). At nine months post-surgery, the FB and MB groups exhibited greater knee flexion at initial contact (0%) and during a proportion of terminal swing phase of the gait cycle (90%-100%) compared to the controls. A similar pattern was evident at three months post-surgery, although this was slightly less pronounced and not outside of the 95% confidence intervals at initial contact.

In the discrete variables, the FB group was found to stair descend with a greater minimum knee flexion ($F_{2,18} = 7.98$; $p<0.05$), in addition to a reduced sagittal knee ROM ($F_{2,18} = 4.11$; $p<0.05$) compared to controls at three months post-surgery (Table 50). The MB group stair descended with increased minimum knee flexion ($F_{2,18} = 7.98$; $p<0.05$), with a reduction in maximum knee flexion ($F_{2,18} = 4.04$; $p<0.05$) and sagittal knee ROM ($F_{2,18} = 4.11$; $p<0.05$) compared to controls. The MB group also stair descended with reduced maximum knee flexion ($F_{2,18} = 4.04$; $p<0.05$; FB=93.2±4.69°; MB=83.1 ±2.76°) and sagittal knee ROM ($F_{2,18} = 4.11$; $p<0.05$;

FB=73.1 ±4.10°; MB=59.8 ±6.89°) compared to the FB group. The FB ($F_{2,18}$ = 7.98; p<0.05) and MB ($F_{2,18}$ = 7.98; p<0.05) groups stair descended with increased minimum knee flexion than controls at nine months post-surgery. No differences were observed between FB and MB prostheses at this time point.

Five conditions reached significance in the within-group between time point analysis (Table 51). Minimum knee flexion ($F_{1.25,15.03}$ = 46.1; p<0.05) increased from pre-surgery to three months post-surgery in the FB group during stair descent, with a reduction in the sagittal knee ROM ($F_{2,24}$ = 12.2; p<0.05). Between pre-surgery and nine months post-surgery, minimum knee flexion ($F_{1.25,15.03}$ = 46.1; p<0.05) increased and sagittal knee ROM ($F_{2,24}$ = 12.2; p<0.05) decreased in the FB group. Sagittal knee ROM ($F_{2,24}$ = 12.2;p<0.05) increased from three months post-surgery to nine months post-surgery in the MB group.

6.3.3 Knee kinetic

6.3.3.1 Stair ascent

Pairwise comparisons are presented in Table 52 relating to the differences between FB, MB, and control groups in kinetic variables during stair ascent at pre-surgery, three months post-surgery, and nine months post-surgery. Table 52 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the kinetic variables during stair ascent.

Table 52 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of kinetic variables at pre-surgery, three months post-surgery, and nine months post-surgery time points during stair ascent

Stair ascent		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Max knee ext. moment (Nm/kg)	-0.42	0.41	-0.22	0.07	-0.45	0.14	$p = 0.07$		-	N/A	N/A
	Max knee flx. moment (Nm/kg)	0.50	0.45	0.78	0.12	0.94	0.36	$p = 0.16$		-	N/A	N/A
	Knee flx at max ext. moment (°)	42.0	27.6	26.8	17.7	28.6	28.1	$p = 0.17$		-	N/A	N/A
	Knee flx at max flx. moment (°)	64.1	19.4	50.3	3.40	49.9	5.95	$p = 0.78$		-	N/A	N/A
	Max knee ab. moment (Nm/kg)	-0.06	0.06	-0.05	0.04	-0.10	0.08	$p = 0.63$		-	N/A	N/A
	Max knee add. moment (Nm/kg)	0.23	0.20	0.40	0.02	0.39	0.14	$p = 0.39$		-	N/A	N/A
	Max knee ext. rot. moment (Nm/kg)	-0.01	0.01	-0.02	0.00	-0.05	0.04	$p = 0.60$		-	N/A	N/A
	Max knee int. rot. moment (Nm/kg)	0.14	0.15	0.12	0.01	0.11	0.07	$p = 0.61$		-	N/A	N/A
Three months post-surgery	Max knee ext. moment (Nm/kg)	-0.26	0.13	-0.27	0.03	-0.45	0.14	$p = 0.07$		-	N/A	N/A
	Max knee flx. moment (Nm/kg)	0.62	0.07	0.84	0.16	0.94	0.36	$p = 0.16$		-	N/A	N/A
	Knee flx at max ext. moment (°)	50.1	15.5	54.2	9.05	28.6	28.1	$p = 0.17$		-	N/A	N/A
	Knee flx at max flx. moment (°)	36.2	23.3	52.0	5.63	49.9	5.95	$p = 0.78$		-	N/A	N/A
	Max knee ab. moment (Nm/kg)	-0.13	0.07	-0.09	0.05	-0.10	0.08	$p = 0.63$		-	N/A	N/A
	Max knee add. moment (Nm/kg)	0.19	0.08	0.30	0.21	0.39	0.14	$p = 0.39$		-	N/A	N/A
	Max knee ext. rot. moment (Nm/kg)	-0.05	0.06	-0.02	0.01	-0.05	0.04	$p = 0.60$		-	N/A	N/A
	Max knee int. rot. moment (Nm/kg)	0.06	0.02	0.11	0.02	0.11	0.07	$p = 0.61$		-	N/A	N/A
Nine months post-surgery	Max knee ext. moment (Nm/kg)	-0.36	0.09	-0.26	0.03	-0.45	0.14	$p = 0.07$		-	-	-
	Max knee flx. moment (Nm/kg)	0.88	0.17	1.01	0.28	0.94	0.36	$p = 0.16$		-	-	-
	Knee flx at max ext. moment (°)	52.2	21.6	22.3	1.09	28.6	28.1	$p = 0.17$		-	-	-
	Knee flx at max flx. moment (°)	40.8	12.7	54.3	6.21	49.9	5.95	$p = 0.78$		-	-	-
	Max knee ab. moment (Nm/kg)	-0.17	0.08	-0.17	0.20	-0.10	0.08	$p = 0.63$		-	-	-
	Max knee add. moment (Nm/kg)	0.24	0.16	0.35	0.24	0.39	0.14	$p = 0.39$		-	-	-
	Max knee ext. rot. moment (Nm/kg)	-0.10	0.07	-0.11	0.15	-0.05	0.04	$p = 0.60$		-	-	-
	Max knee int. rot. moment (Nm/kg)	0.08	0.10	0.08	0.09	0.11	0.07	$p = 0.61$		-	-	-

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic); 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Table 53 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of kinetic variables in fixed bearing (FB) and mobile bearing (MB) patients during stair ascent

Stair ascent		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Max knee ext. moment (Nm/kg)	$p = 0.66$	0.24	-	-	-
	Max knee flx. moment (Nm/kg)	$\boldsymbol{p < 0.05}$	4.13	1.00	*	*
	Knee flx at max ext. moment (°)	$p = 0.15$	2.30	-	-	-
	Knee flx at max flx. moment (°)	$p = 0.07$	2.99	-	-	-
	Max knee ab. moment (Nm/kg)	$\boldsymbol{p < 0.05}$	4.39	*	1.00	0.14
	Max knee add. moment (Nm/kg)	$p = 0.62$	0.48	-	-	-
	Max knee ext. rot. moment (Nm/kg)	$\boldsymbol{p < 0.05}$	5.35	0.09	0.73	0.06
	Max knee int. rot. moment (Nm/kg)	$p = 0.34$	1.14	-	-	-
MB	Max knee ext. moment (Nm/kg)	$p = 0.66$	0.24	N/A	N/A	N/A
	Max knee flx. moment (Nm/kg)	$\boldsymbol{p < 0.05}$	4.13	N/A	N/A	N/A
	Knee flx at max ext. moment (°)	$p = 0.15$	2.30	N/A	N/A	N/A
	Knee flx at max flx. moment (°)	$p = 0.07$	2.99	N/A	N/A	N/A
	Max knee ab. moment (Nm/kg)	$\boldsymbol{p < 0.05}$	4.39	N/A	N/A	N/A
	Max knee add. moment (Nm/kg)	$p = 0.62$	0.48	N/A	N/A	N/A
	Max knee ext. rot. moment (Nm/kg)	$\boldsymbol{p < 0.05}$	5.35	N/A	N/A	N/A
	Max knee int. rot. moment (Nm/kg)	$p = 0.34$	1.14	N/A	N/A	N/A

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

No differences were found between FB and MB prostheses at nine months post-surgery, with the MB group excluded from the pre-surgery and three months post-surgery analysis as an insufficient number of patients were able to adequately perform the stair ascent activity (n=3 and n=4, respectively) (Table 52).

The FB group in the within-group between time point analysis exhibited an increase in the maximum knee abduction moment ($F_{1.28,15.31} = 4.39$; $p<0.05$) from pre-surgery to three months post-surgery during stair ascent (Table 53). In addition, the FB group displayed an increase in the maximum knee flexion moment ($F_{2,24} = 4.13$; $p<0.05$) from three months post-surgery to nine months post-surgery. The FB group also presented an increase in the maximum knee flexion moment ($F_{2,24} = 4.13$; $p=0.05$) from pre-surgery to nine months post-surgery.

6.3.5.3 Stair descent

Pairwise comparisons are presented in Table 54 relating to the differences between FB, MB, and control groups in kinetic variables during stair descent at pre-surgery, three months post-surgery, and nine months post-surgery. Table 55 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the kinetic variables during stair descent.

Table 54 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of kinetic variables at pre-surgery, three months post-surgery, and nine months post-surgery time points in stair descent

Stair descent		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Max knee ext. moment (Nm/kg)	-0.16	0.10	-0.09	N/A	-0.38	0.08	$p = 0.45$	0.84	-	N/A	N/A
	Max knee flx. moment (Nm/kg)	1.21	0.68	0.88	N/A	1.02	0.19	$p = 0.50$	0.60	-	N/A	N/A
	Knee flx at max ext. moment (°)	25.6	15.9	16.2	N/A	16.7	6.76	$\boldsymbol{p < 0.05}$	7.15	0.50	N/A	N/A
	Knee flx at max flx. moment (°)	58.1	17.2	59.8	N/A	45.0	13.7	$p = 0.07$	3.12	-	N/A	N/A
	Max knee ab. moment (Nm/kg)	-0.08	0.05	-0.02	N/A	-0.08	0.03	$p = 0.33$	1.17	-	N/A	N/A
	Max knee add. moment (Nm/kg)	0.42	0.28	0.56	N/A	0.40	0.16	$p = 0.46$	0.80	-	N/A	N/A
	Max knee ext. rot. moment (Nm/kg)	-0.09	0.10	-0.01	N/A	-0.07	0.04	$p = 0.96$	0.04	-	N/A	N/A
	Max knee int. rot. moment (Nm/kg)	0.07	0.07	0.05	N/A	0.09	0.06	$p = 0.37$	1.05	-	N/A	N/A
Three months post-surgery	Max knee ext. moment (Nm/kg)	-0.24	0.16	-0.22	0.11	-0.38	0.08	$p = 0.45$	0.84	-	-	-
	Max knee flx. moment (Nm/kg)	0.68	0.40	1.21	0.15	1.02	0.19	$p = 0.50$	0.60	-	-	-
	Knee flx at max ext. moment (°)	23.2	3.66	27.9	0.74	16.7	6.76	$\boldsymbol{p < 0.05}$	7.15	0.19	0.08	1.00
	Knee flx at max flx. moment (°)	51.3	13.6	44.7	10.0	45.0	13.7	$p = 0.07$	3.12	-	-	-
	Max knee ab. moment (Nm/kg)	-0.10	0.08	-0.22	0.23	-0.08	0.03	$p = 0.33$	1.17	-	-	-
	Max knee add. moment (Nm/kg)	0.19	0.14	0.17	0.12	0.40	0.16	$p = 0.46$	0.80	-	-	-
	Max knee ext. rot. moment (Nm/kg)	-0.05	0.04	-0.09	0.04	-0.07	0.04	$p = 0.96$	0.04	-	-	-
	Max knee int. rot. moment (Nm/kg)	0.04	0.02	0.01	0.00	0.09	0.06	$p = 0.37$	1.05	-	-	-
Nine months post-surgery	Max knee ext. moment (Nm/kg)	-0.54	0.33	-0.46	0.37	-0.38	0.08	$p = 0.45$	0.84	-	-	-
	Max knee flx. moment (Nm/kg)	0.86	0.32	1.01	0.33	1.02	0.19	$p = 0.50$	0.60	-	-	-
	Knee flx at max ext. moment (°)	19.7	3.11	23.6	4.24	16.7	6.76	$\boldsymbol{p < 0.05}$	7.15	1.00	0.45	1.00
	Knee flx at max flx. moment (°)	52.2	11.5	59.9	11.0	45.0	13.7	$p = 0.07$	3.12	-	-	-
	Max knee ab. moment (Nm/kg)	-0.16	0.19	-0.04	0.14	-0.08	0.03	$p = 0.33$	1.17	-	-	-
	Max knee add. moment (Nm/kg)	0.38	0.21	0.40	0.13	0.40	0.16	$p = 0.46$	0.80	-	-	-
	Max knee ext. rot. moment (Nm/kg)	-0.11	0.11	-0.26	0.33	-0.07	0.04	$p = 0.96$	0.04	-	-	-
	Max knee int. rot. moment (Nm/kg)	0.07	0.03	0.05	0.15	0.09	0.06	$p = 0.37$	1.05	-	-	-

'SD' equates to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

Table 55 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of kinetic variables in fixed bearing (FB) and mobile bearing (MB) patients during stair descent

Stair descent		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Max knee ext. moment (Nm/kg)	***p* < 0.05**	7.99	0.50	*	*
	Max knee flx. moment (Nm/kg)	*p* = 0.81	0.22	-	-	-
	Knee flx at max ext. moment (°)	*p* = 0.38	0.90	-	-	-
	Knee flx at max flx. moment (°)	*p* = 0.13	2.48	-	-	-
	Max knee ab. moment (Nm/kg)	*p* = 0.18	2.01	-	-	-
	Max knee add. moment (Nm/kg)	***p* < 0.05**	13.0	*	*	1.00
	Max knee ext. rot. moment (Nm/kg)	*p* = 0.05	4.34	NS	-	NS
	Max knee int. rot. moment (Nm/kg)	*p* = 0.15	2.03	NS	NS	NS
MB	Max knee ext. moment (Nm/kg)	***p* < 0.05**	7.99	N/A	0.51	N/A
	Max knee flx. moment (Nm/kg)	*p* = 0.81	0.22	N/A	-	N/A
	Knee flx at max ext. moment (°)	*p* = 0.38	0.90	N/A	-	N/A
	Knee flx at max flx. moment (°)	*p* = 0.13	2.48	N/A	-	N/A
	Max knee ab. moment (Nm/kg)	*p* = 0.18	2.01	N/A	-	N/A
	Max knee add. moment (Nm/kg)	***p* < 0.05**	13.0	N/A	*	N/A
	Max knee ext. rot. moment (Nm/kg)	*p* = 0.05	4.34	N/A	-	N/A
	Max knee int. rot. moment (Nm/kg)	*p* = 0.15	2.03	N/A	NS	N/A

'Sig.' equates to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. <5 of 8 participants in each group)'

No differences were observed between-groups at pre-surgery, three months post-surgery, and nine months post-surgery in the discrete variables (Table 54). Differences were evident in the within-group between time point analysis (Table 55). The FB group displayed a reduction in the maximum knee adduction moment ($F_{2,24}$ = 13.0; p<0.05) from pre-surgery to three months post-surgery. A reduction was also apparent in the maximum knee extension moment ($F_{1.35,16.18}$ = 7.99; p<0.05), in addition to an increase in the maximum knee adduction moment ($F_{2,24}$ = 13.0; p<0.05) from three months post-surgery to nine months post-surgery. A reduction in the maximum knee extension moment ($F_{1.35,16.18}$ = 7.99; p<0.05) from pre-surgery to nine months post-surgery was also observed.

6.3.4 Maximum knee angular velocity and loading ratio

Pairwise comparisons are presented in Table 56 relating to the differences between FB, MB, and control groups in maximum knee angular velocity and loading ratio variables during sit to stand and stand to sit at pre-surgery, three months post-surgery, and nine months post-surgery. Table 56 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the maximum knee angular velocity and loading ratio variables.

Table 56 – Fixed bearing (FB), mobile bearing (MB), and control participant between-group differences of kinetic variables at pre-surgery, three months post-surgery, and nine months post-surgery time points in sit to stand and stand to sit

Sit to stand and stand to sit		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Sit to stand max ext velocity (°/s)	-72.4	20.8	-85.0	32.6	-136	41.4	***p* < 0.05**	9.51	*	0.08	1.00
	Sit to stand loading ratio	0.83	0.14	0.75	0.14	1.22	0.24	***p* < 0.05**	12.1	*	*	1.00
	Stand to sit max flx velocity (°/s)	71.2	30.2	60.3	10.8	98.1	17.9	***p* < 0.05**	6.86	0.11	*	1.00
	Stand to sit loading ratio	0.85	0.21	0.78	0.20	1.07	0.12	***p* < 0.05**	5.23	0.09	*	0.29
Three months post-surgery	Sit to stand max ext velocity (°/s)	-92.7	13.4	-108	33.6	-136	41.4	***p* < 0.05**	9.51	0.07	-	-
	Sit to stand loading ratio	0.76	0.11	0.91	0.11	1.22	0.24	***p* < 0.05**	12.1	*	N/A	N/A
	Stand to sit max flx velocity (°/s)	65.5	18.4	79.2	23.2	98.1	17.9	***p* < 0.05**	6.86	*	0.35	0.74
	Stand to sit loading ratio	0.96	0.17	0.91	0.15	1.07	0.12	***p* < 0.05**	5.23	0.56	0.21	1.00
Nine months post-surgery	Sit to stand max ext velocity (°/s)	-107	20.5	-60.7	79.9	-136	41.4	***p* < 0.05**	9.51	0.83	0.06	0.37
	Sit to stand loading ratio	0.89	0.18	1.14	0.29	1.22	0.24	***p* < 0.05**	12.1	0.07	1.00	0.34
	Stand to sit max flx velocity (°/s)	96.4	36.6	79.5	19.4	98.1	17.9	***p* < 0.05**	6.86	1.00	0.76	0.89
	Stand to sit loading ratio	1.17	0.16	1.00	0.22	1.07	0.12	***p* < 0.05**	5.23	0.88	1.00	0.29

'ext' equates to 'Extension'; 'SD' to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*p*' to '*p* value'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. < 5 of 8 participants in each group)'; 'flx' to 'Flexion'

Table 57 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of kinetic variables in fixed bearing (FB) and mobile bearing (MB) patients during sit to stand and stand to sit

Sit to stand and stand to sit		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	Sit to stand max ext velocity (°/s)	$p = 0.31$	1.17	-	-	-
	Sit to stand loading ratio	$\boldsymbol{p < 0.05}$	6.76	0.79	0.07	1.00
	Stand to sit max flx velocity (°/s)	$p = 0.08$	2.69	-	-	-
	Stand to sit loading ratio	$\boldsymbol{p < 0.05}$	10.7	0.32	*	*
MB	Sit to stand max ext velocity (°/s)	$p = 0.31$	1.17	N/A	N/A	-
	Sit to stand loading ratio	$\boldsymbol{p < 0.05}$	6.76	N/A	N/A	*
	Stand to sit max flx velocity (°/s)	$p = 0.08$	2.69	-	-	-
	Stand to sit loading ratio	$\boldsymbol{p < 0.05}$	10.7	0.43	0.24	0.07

'ext' equates to 'Extension'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; 'PS' to 'Post-surgery'; '*' to 'Significant at the 0.05 level'; 'N/A' to 'Not applicable due to there being insufficient data through the participants inability to adequately perform the required movements (i.e. < 5 of 8 participants in each group)'; 'flx' to 'Flexion'

At pre-surgery, differences were observed in the FB group with a reduction in both the sit to stand maximum knee extension velocity ($F_{2,28} = 9.51$; $p<0.05$) and the sit to stand loading ratio ($F_{2,26} = 12.1$; $p<0.05$) when compared to controls (Table 56). The MB group displayed reductions in the sit to stand loading ratio ($F_{2,26} = 12.1$; $p<0.05$), stand to sit maximum knee flexion velocity ($F_{2,30} = 6.86$; $p<0.05$), and stand to sit loading ratio ($F_{2,30} = 5.23$; $p<0.05$) when compared to controls. No differences were observed between FB and MB groups. The FB group at three months post-surgery exhibited reductions in the sit to stand loading ratio ($F_{2,26} = 12.1$; $p<0.05$) and stand to sit maximum knee flexion velocity when compared to controls ($F_{2,30} = 6.86$; $p<0.05$). No differences were observed between FB and MB groups at three or nine months post-surgery.

In the within-group between time point analysis, an increase was found in the stand to sit loading ratio ($F_{2,32} = 10.7$; $p<0.05$) from three months post-surgery to nine months post-surgery in the FB group (Table 57). The stand to sit loading ratio ($F_{2,32} = 10.7$; $p<0.05$) also improved from pre-surgery to nine months post-surgery. The MB group exhibited an increase in the sit to stand loading ratio ($F_{1.23,17.25} = 6.76$; $p<0.05$) from pre-surgery to nine months post-surgery.

6.4 Discussion

Due to the observation of no differences between FB and MB groups during level walking (Chapter 5), the aim of this chapter was to analyse whether MB total knee prostheses offered biomechanical advantages when compared to FB designs during more demanding activities. In addition, the previous findings of instability in MB prostheses during stair negotiation were investigated [29, 79]. This chapter was unable to identify any differences ($p<0.05$; >MDC) between FB and MB groups during stair ascent, stair descent, sit to stand, or stand to sit activities at nine months post-surgery, refuting both the contrasting suggestions of biomechanical advantages and instability in MB designs.

Theoretically, due to the increased magnitude of knee flexion during stair negotiation [187], MB prostheses have greater capacity to optimise ROM compared to walking. In the normal knee, the amount of axial rotation is approximately 30° through 120° of knee flexion [15]. There is a potentially greater relative benefit of MB implantation during stair negotiation due to the activity requiring 75°-80° of maximum knee flexion following TKR [190], which is approximately 15°-20° greater than walking [183, 187]. Contrary to these biomechanical advantages, the findings of the current study were unable to determine any advantages of MB implantation.

Despite there being no differences between FB and MB prostheses at nine months post-surgery, the MB group stair descended with reduced ($p<0.05$; >MDC) maximum knee flexion and sagittal ROM than the FB group at three months post-surgery. The addition of pre-surgery testing, however, suggested this difference was apparent prior to surgery and not a result of prosthetic design. No statistical analysis was undertaken to confirm this due to the small number of patients able to adequately perform the activity at pre-surgery. These results are consistent with the previous limited findings of no biomechanical advantages of MBs during stair negotiation [29, 79].

A further finding of note at nine months post-surgery was the observation of the MB group having a greater ($p<0.05$; >MDC) minimum knee flexion angle than controls during stair ascent, a difference not apparent in the FB group. The addition of pre-surgery testing, however, suggested this difference was apparent prior to surgery, although not to the magnitude observed at nine months post-surgery and less than the MDC values. The patients able to adequately perform stair ascent at pre-surgery were also likely to be the better performing patients, and thus the addition of the remaining patients may have led to greater differences at pre-surgery, thus supporting the assertion of no meaningful difference at nine months post-surgery.

In a published abstract comparing FB and MB prostheses, Azzopardi et al. [237] presented results in favour of MBs. The authors found reduced knee internal rotation moments during walking in MB prostheses (FB=0.14Nm/kg; MB=0.09Nm/kg; p=0.094), with this difference amplified during an unspecified deep knee bend activity. The authors concluded that the kinematic and kinetic differences between the groups reflect different patterns of joint surface motion and loading, with postulated beneficial effects for MBs relating to improved long term failure through reduced wear and component loosening. No further information was presented, however, with no full paper published. Other authors applying fluoroscopic analyses have also detailed optimised axial ROM, with Dennis et al. [238] reporting that 80% of MB posterior stabilised knees demonstrated normal axial rotation patterns, with a mean ROM of 3.9° in a multicenter analysis. Ranawat et al. [57] also reported that 18 of 20 patients who had the Sigma Rotating Platform Knee System (De Puy, Warsaw, IN, USA), the prosthesis used in this thesis, experienced a normal pattern of axial rotation of 7.3°. Despite these findings, no differences in the current study were found in the axial plane knee joint kinematics or kinetics between FB and MB groups.

As determined in Chapter 2, Catani et al. [29] and Fantozzi et al. [79] previously detailed differences between FB and MB prostheses during stair negotiation. Fantozzi et al. [79] found the MB group ascended with reduced gait velocity than the FB group, although this could be attributed to the MB group being older and heavier, and is therefore not likely to be related to prosthetic design. In addition, no pre-surgery data were provided in order to determine the likelihood of this. No differences in gait velocity were observed between the FB and MB groups in the current study, with the groups well matched at baseline in age, gender, height, and weight.

This study was also unable to replicate the findings of instability in Catani et al. [29] and Fantozzi et al. [79] through reduced maximum knee extension and adduction moments. One potential reason for this is that differences were apparent in the MB designs used. The MBK prosthesis (Mobile bearing, Zimmer, Warsaw, IN, USA) utilised in Catani et al. [29] allows 3mm of antero-posterior translation, a design which is aimed at ligament controlled kinematics of the knee and is used in a posterior cruciate ligament (PCL) retaining scenario. Similar antero-posterior displacement is permitted in the Interax ISA prosthesis (Mobile bearing, Stryker Orthopaedics, Limerick, Ireland) used in Fantozzi et al. [79], with 9mm of translation. The Sigma Rotating Platform Knee System (De Puy International, Leeds, UK) (Figures 2 and 3) used in this thesis, however, is constrained to axial rotation at the bearing interface, although some residual translation is still possible between the femoral component and the dished profiles of the tibial insert.

The importance of this is highlighted by Catani et al. [29] and Fantozzi et al. [79] who found that the antero-posterior translating MB knees behaved like cruciate sacrificing knees during mid to terminal stance phase when the knee approaches full extension. At this point, O'Connor [239] has detailed that muscle forces parallel to the tibial plateau pull the tibia anteriorly, causing posterior displacement of the femur. In the MB designs that allow antero-posterior translation, this action may cause the knee to flex slightly, thus reducing the knee extension moment in a 'buckling' movement. Catani et al. [29] found that a proprioceptive response to this instability was to prolong the activation of the rectus femoris towards terminal stance phase.

Although no differences were found between FB and MB groups, a similar trend was observed in the current study, with both prosthesis groups showing an increased flexion trend compared to controls during mid to terminal stance phase following TKR surgery (Figure 12). This supports the assertion of increased quadriceps activity in order to stabilise the knee in the absence of optimised anterior stability during stair ascent. Unsurprisingly, this pattern was also observed during stair descent at initial contact and early loading response, in addition to terminal swing (Figure 13). Stair descent is considered as a more challenging activity than stair ascent as stability is more dependent on quadriceps function [192, 193], which is evidenced through the greater absolute knee flexion moments [240]. The reliance upon greater quadriceps activity for stability is problematic following surgery due to the loss of quadriceps strength, which is predominately attributed to the failure of voluntary muscle activation [241].

An important limiting factor with the evidence presented in Catani et al. [29] and Fantozzi et al. [79] is that different PCL scenarios were implemented between the prosthesis designs. An advantage of the protocol used within this thesis is that the same scenario was utilised in both prostheses, with the PCL substituted and a post and cam mechanism used to provide posterior stability. A number of authors have detailed advantages of posterior stabilised designs over PCL retention with regards to a more stable component interface [95, 96] and increased ROM [90, 95-98]. These findings suggest that not controlling for different PCL scenarios may introduce bias into the comparison of FB and MB designs. No consistency was apparent in Catani et al. [29] and Fantozzi et al. [79], with Catani et al. [29] utilising a posterior stabilised design in the FB group and a PCL retaining design in the MB group, and Fantozzi et al. [79] utilising a PCL retaining design in the FB group and a posterior stabilised design in the MB group.

Sit to stand and stand to sit activities were employed to examine the effect of potential instability in MB knees on contralateral loading, which is a precursor for osteoarthritic progression [242]. Sit to stand is one of the most important ADLs [243-245] as it is often undertaken prior to walking [246] and performed many times per day [245, 247]. No previous studies have compared FB and MB prostheses during sit to stand or stand to sit movements, although studies have assessed unilateral TKR patients during sit to stand movements [83, 156, 204-206, 248, 249]. Four previous studies have also included the loading symmetry ratio as the primary biomechanical variable [204-206, 250], supporting the importance of assessing contralateral loading.

In support of the findings during stair negotiation, no differences ($p>0.05$; <MDC) were found between FB and MB groups at any time point. Differences ($p>0.05$; <MDC) were highlighted, however, between the TKR patients and controls. In this instance, the sit to stand and stand to sit loading ratios may be misleading in the controls as the groups exhibited magnitudes of 1.22 ±0.24 and 1.07 ±0.12, respectively, indicating a greater contribution from the non-dominant leg, thus skewing the ratio. In reality, this ratio is 0.78 in sit to stand, and 0.93 in stand to sit, with 1 being indicative of a perfect loading symmetry. The significant findings can be attributed to this, and in reality, this was not apparent, with no differences between the grouped TKR and control groups at pre-surgery (adjusted; FB=0.83 ±0.14; MB=0.75 ±0.14; control = 0.78 ±0.24), three months post-surgery (adjusted; FB=0.76 ±0.11; MB=0.91 ±0.11; control = 0.78 ±0.24), or nine months post-surgery (adjusted; FB=0.89 ±0.18; MB=1.14 ±0.29; control = 0.78 ±0.24) that were greater than the MDC magnitudes presented in Chapter 4 when adjusted in the sit to stand results.

At pre-surgery in the stand to sit results, the MB group exhibited a reduced loading ratio compared to controls (MB=0.78 ±0.20; control = 1.07 ±0.12; $df=_{2,30}$; $p<0.05$). When adjusted, no differences were observed that were greater than the MDC magnitudes presented in Chapter 4 (MB=0.78 ±0.20; control = 0.93 ±0.12). These results suggest no significant asymmetry in the loading of the affected leg during biomechanically demanding activities compared to controls. This is an important factor for limiting OA progression in the contralateral leg, as well as suggesting no instability.

Despite this, both FB and MB groups demonstrated improved ($p>0.05$) sit to stand and stand to sit loading ratios, respectively, from pre-surgery to nine months post-surgery, although only the sit to stand loading ratio in MB group was greater than the MDC values. The combination of quadriceps weakness [205] and knee pain [251] are likely to be the major contributing factors to the reduced ipsilateral loading, in addition to contributing to the reduced maximum knee extension velocity in the patient groups at pre-surgery. Knee pain is likely to be limited to the pre-surgery condition [204, 252], although quadriceps weakness has been shown to persist following TKR, due in part to the reduced loading not stimulating the quadriceps musculature

[204, 253]. Factors other than quadriceps weakness post-surgery, such as fear or unresolved habitual movement patterns, may also be associated with loading asymmetry [250]. The findings of the current study are in agreement with previous reports that suggest asymmetry is typically resolved at six months post-surgery [156, 204, 205].

6.4.1 Limitations

A limitation of this study is the MB group was excluded from the statistical analyses due to an inadequate (<5) amount of patients being able to adequately perform stair ascent at pre-surgery and three months post-surgery, in addition to stair descent at pre-surgery without the use of supportive handrails. Reliance upon handrail use is not uncommon in patients prior to TKR surgery, with Zeni and Snyder-Mackler [254] documenting that 63 out of 105 patients required a handrail in a study investigating pre-surgery predictors of post-surgery impairment. Two years after surgery, 60 of the 105 patients (57.14%) still required a handrail for assistance during stair negotiation. The use of instrumented handrails could be employed as a solution to measure the amount of force applied, although the differing magnitude and direction of force between individuals would make standardisation difficult. As well as affecting force, handrail use has also been shown to modify spatiotemporal variables [255]. This would have further confounded any comparisons if these patients were included in the current study, supporting the exclusion of these data.

The employed ‘step over step’ technique may have been too demanding for the patients with late stage knee OA at pre-surgery, and with a compromised rehabilitation status at three months post-surgery. There are other methods used in the literature such as increased handrail use, sideways motion, or a step-by-step pattern in which the individual places both feet on the same step before ascending or descending [182]. Despite the biomechanical difficulty, the ‘step over step’ method reinforces good practice as deviations from this result in higher energy costs, lower efficiency, and an increased risk of falling [256-258]. An increased risk of falling has important implications to everyday living as it can lead to serious injury and death among older adults [259].

It could also be interpreted from this finding that the groups were not well matched at pre-surgery. There were however, as presented in Chapter 5, no differences between groups in the Oxford Knee Score [225] at pre-surgery, suggesting otherwise. There may have been inherent differences between groups in motivation or pain threshold that were not accounted for, but could also affect an individual's ability to undertake the activity when in considerable discomfort.

A limitation of the continuous waveforms illustrated in Figures 12 and 13 is the effect that averaging the curves of individual patients, with potentially different gait patterns, has on the depicted curve presented in the figures. Patients in the same experimental group with differing proportions of stance and swing phases of gait will experience gait events at different percentages in the gait cycle, for example, maximum knee flexion during swing. The averaging of the continuous waveforms in these instances creates a dampening effect, for example, depicting a lower mean maximum knee flexion during swing than what was observed. Although the continuous waveforms are useful for illustrative purposes, reference to the specific point parameters in Tables 48 and 50 should be made for true values.

Due to the differences between the patient groups and controls in body mass and BMI as discussed in Chapter 5, this could have also led to differences in ROM between the groups in stair negotiation and sit to stand and stand to sit activities. Gait velocity during stair negotiation also differed between the patient groups and controls which could have also contributed to differences in other spatiotemporal variables and ROM. The overarching aim of this study, however, was to compare FB and MB groups. The patient groups had similar (p>0.05) body mass and BMI measurements, in addition to ambulating with similar (p>0.05) gait velocity. This supports the main comparison of FB and MB groups in the current study.

6.5 Conclusions

- Despite the greater biomechanical difficulty, no differences were found between FB and MB groups that could not be explained by differences at pre-surgery.
- There was no evidence of instability in MB knees during stair negotiation, sit to stand, or stand to sit.

- FB and MB groups exhibited greater knee flexion in proportions of stance phase during both stair ascent and stair descent following surgery, suggesting the reliance upon increased quadriceps activity in order to stabilise the knee.

7.0 Validation and reliability of electrogoniometry and accelerometry for measuring knee kinematics and physical activity during free living conditions

7.1 Introduction

Testing in the gait laboratory over a range of activities of daily living (ADLs) was unable to identify any biomechanical advantages of implantation with mobile bearing (MB) total knee prostheses in Chapters 5 and 6. The biomechanics of the knee have been traditionally measured under laboratory conditions. Although this approach is useful for quantitative measurements and experimental studies [72], laboratory testing may not always be clinically valid as it is not exclusively representative of everyday living [82]. As a result, problems can arise when extrapolating the results for interpretation outside of the laboratory.

There is a wider requirement in the field of knee biomechanics for research that optimises clinical applicability [72]. Rowe et al. [72] suggested the need to respond to an increasing demand for the development of a method which establishes the dynamic function of a joint. The measurement of patients away from the laboratory in the field setting can provide data on rehabilitation status [135], with the potential for the method to become a tool in the evaluation of joint function following surgical interventions.

Such implementation of remote monitoring following total knee replacement (TKR) surgery is undoubtedly attractive. In addition to costs relating to hospital stay following TKR, there is a substantial cost implication due to continuing care and monitoring throughout the post-surgery period [261, 262]. Monitoring patient recovery in outpatient clinics is both labour intensive, and possibly inaccurate given that it relies to a large extent on clinical examinations and subjective clinical questionnaires [263]. Patients are also often asked to attend regular rehabilitation sessions and keeping track of progress over time incurs a considerable healthcare cost.

An instrument capable of undertaking remote kinematic monitoring is the electrogoniometer. Electrogoniometry systems can provide detailed information on knee function through the continuous measurement of kinematics [152], and as a result, have been used to measure sagittal knee kinematics during ADLs [72, 152, 153, 190, 191, 264-266]. This has been undertaken in asymptomatic [72, 153] and clinical populations; in particular within the assessment of knee kinematics following osteoarthritic degeneration [152, 191] and subsequent TKR surgery [152, 184, 190, 265, 266]. In addition, these instruments have also been shown to exhibit greater sensitivity than clinical questionnaires when detecting changes in gait [267]. Despite the growing use of electrogoniometry, few authors have measured participants away from observation during free living conditions [82, 146, 268], with no standardised protocol developed.

The aim of this chapter was threefold:

- Experiment (1): To concurrently assess the validity of electrogoniometry during specific ADLs in the laboratory with a view to using the system to compare the kinematics of fixed bearing (FB) and MB groups during free living conditions in Chapter 8.
- Experiment (2): To assess the between-session reliability and minimum detectable change (MDC) of sagittal knee kinematics using electrogoniometry and physical activity using accelerometry during free living conditions.
- Experiment (3): To assess the between-session reliability and MDC of electrogoniometry during specific ADLs in the laboratory to accurately infer whether potential differences in between-session reliability in Experiment 2 were attributable to poor reliability of the electrogoniometer or to differences in physical activity between-sessions.

This chapter has been published, in part, within the Journal of Musculoskeletal Research, the Proceedings of the American Society of Biomechanics, and the Proceedings of the 2nd International Conference on Ambulatory Measurement of Physical Activity and Movement.

7.2 Method

7.2.1 Participants

Ten control participants were recruited from advertisements and informal contacts at Northumbria University. All participants were male and had a mean age of 23.1 ±3.69yrs, height of 1.79 ±0.07m, mass of 81.57 ±7.79kg, and body mass index (BMI) of 25.42 ±2.21kg/m^2. The exclusion criteria were previous knee or hip replacement, current lower limb injury, previous conditions, operations, or other condition which could have had the potential to affect ambulation. Due to the accuracy required for validation purposes in Experiment 1, participants were excluded if they had a BMI of ≥30.00kg/m^2, a classification defined as ‘obese’ by the World Health Organisation [216].

7.2.2 Instrumentation set-up and protocol

7.2.2.1 Experiment 1 – Validation of the electrogoniometry system

The instrumentation set-up of the three dimensional motion analysis and electrogoniometry systems were described in Chapter 3 (‘3.2 Three dimensional motion analysis system’ and ‘3.3 Electrogoniometry and accelerometry systems’, respectively). Participants undertook a number of walking, stair ascent, stair decent, sit to stand, and stand to sit trials until three right sided trials suitable for analysis were captured as described in Chapter 3 (‘3.2.1 Activities of daily living protocol used in the three dimensional motion analysis system’). Data from both systems were synchronised and captured simultaneously over the same trials to determine the concurrent validity.

7.2.2.2 Experiment 2 – Reliability of knee kinematics and physical activity between-sessions

The instrumentation set-up of the electrogoniometry and accelerometry systems were described in Chapter 3 (‘3.3.1 Ambulatory protocol used in the electrogoniometry and accelerometry systems for testing away from the laboratory’). The participants were asked to arrive at the laboratory by 7.40am on the day of testing, with measurement beginning at a standardised time of 8.00am. The electrogoniometry and accelerometry systems captured data for eight hours, with the participants returning to the laboratory at 4.00pm for instrument removal. The testing was repeated on the day following, providing two eight hour data sets. Both testing sessions were performed between the week days of Monday to Friday.

7.2.2.3 Experiment 3 – Reliability of the electrogoniometry system

The instrumentation set-up of the electrogoniometry system was described in Chapter 3 (‘3.3 Electrogoniometry and accelerometry systems’). Participants undertook a number of walking, stair ascent, stair decent, sit to stand, and stand to sit trials until three right sided trials suitable for analysis were captured as described in Chapter 3 (‘3.2.1 Activities of daily living protocol used in the three dimensional motion analysis system’). The electrogoniometry system was then removed from the participant, and subsequently re-attached following the same procedures as outlined in Chapter 3 (‘3.3 Electrogoniometry and accelerometry systems’). The foot switches were not removed from the participants between-sessions. Further trials of walking, stair ascent, stair descent, sit to stand, and stand to sit were performed until three suitable for analysis were captured.

7.2.3 Data analysis

7.2.3.1 Experiment 1 – Validation of the electrogoniometry system

Data cleaning and processing in the three dimensional motion analysis and electrogoniometry systems were undertaken in line with the methods described in Chapter 3 (‘3.2.2 Data cleaning and processing in the three dimensional motion analysis system’ and ‘3.3.2 Data cleaning and processing in the in the electrogoniometry and accelerometry systems’, respectively).

Analysis of validity by linear regression was undertaken using a Microsoft Excel (Microsoft, Redmond, WA, USA) spreadsheet [269] for the sagittal right knee angular displacement. Pearson’s correlation coefficient *r* was derived to depict the linear relationship between the electrogoniometer and motion analysis system throughout the displacement cycles of walking, stair ascent, stair descent, sit to stand, and stand to sit. The typical error (TE) and standardised TE (STE) were used to describe the measurement error between the two systems, with these parameters suggested previously for use in validity studies [270, 271]. The STE was interpreted using a modified Cohen scale [157]. The predicted residual sums of squares (PRESS statistic) was also used to calculate the new prediction error of a potential participant drawn randomly from the same population.

Initially, analyses were only undertaken as a mean of the synchronised waveforms. Post-hoc analyses suggested that greater errors were observed at the point of maximum knee flexion between systems. These data were then further analysed at this point across walking, stair ascent, and stair descent.

7.2.3.2 Experiment 2 – Reliability of knee kinematics and physical activity between-sessions

Data cleaning and processing in the electrogoniometry and accelerometry systems were undertaken in line with the methods described in Chapter 3 ('3.3.2 Data cleaning and processing in the in the electrogoniometry and accelerometry systems'). The collated data sets were then imported into a Microsoft Excel spreadsheet for the analysis of between-session reliability [157] for the sagittal right knee angular displacement, sagittal right knee angular velocity, gross acceleration, and number of steps undertaken. Typical error, standardised TE, Pearson's correlation coefficient *r*, and the intraclass correlation (ICC) were derived from the analysis spreadsheet as described in Chapter 4 ('4.2.3 Data analysis'). Minimum detectable change (MDC) was also calculated as described in Chapter 4 ('4.2.3 Data analysis').

7.2.3.3 Experiment 3 – Reliability of the electrogoniometry system

Data cleaning and processing in the electrogoniometry and accelerometry systems were undertaken in line with the methods described in Chapter 3 ('3.3.2 Data cleaning and processing in the in the electrogoniometry and accelerometry systems'). The collated data sets were then imported into a Microsoft Excel spreadsheet for the analysis of between-session reliability [157] relating to the sagittal right knee angular displacement. Typical error, STE, Pearson's correlation coefficient *r*, and the ICC were derived from the analysis spreadsheet. Minimum detectable change was also calculated as described in Chapter 4 ('4.2.3 Data analysis').

7.3 Results

7.3.1 Experiment 1 – Validation of the electrogoniometry system

An example of one participant over one trial during walking is presented in Figure 14 for the measurement of the sagittal right knee angular displacement in the electrogoniometry and three dimensional motion analysis system during walking, stair ascent, stair descent, sit to stand, and stand to sit. This figure depicts greater error at maximum knee flexion during walking, and as a result, this was investigated across all participants over walking, stair ascent, and stair descent.

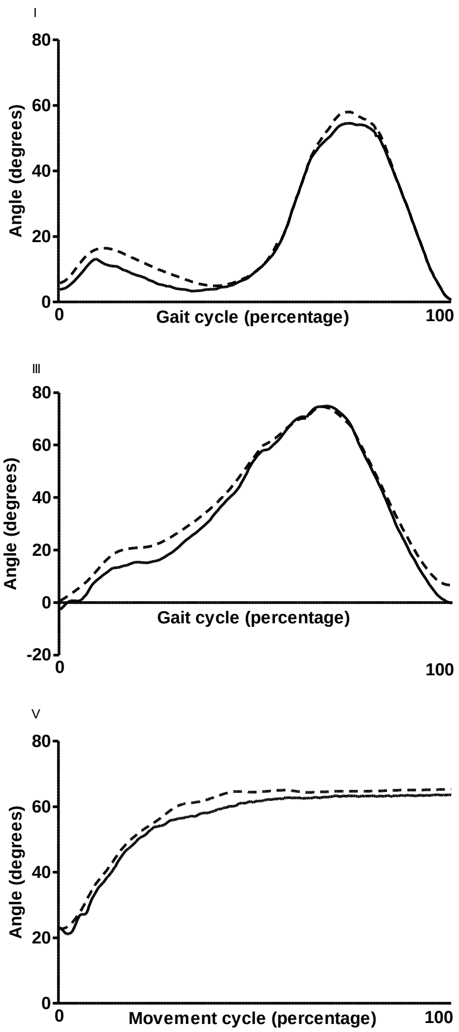

Figure 14 – Raw trace of the right sagittal knee angular displacement as the initial synchronised output of the electrogoniometry (- -) and motion analysis systems (−) of one participant across one trial in level walking (I), stair ascent (II), stair descent (III), sit to stand (IV), and stand to sit (V)

The discrete variables of maximum knee flexion and maximum knee angular velocity, as measured by the electrogoniometry system, are presented in Table 58 to inform the limit of validation.

Table 58 – Maximum knee flexion and maximum knee angular velocity as measured by the electrogoniometry system across walking, stair ascent, stair descent, sit to stand, and stand to sit activities in ten asymptomatic participants to inform the limit of the validation

	Max. knee flexion (°)	SD (°)	Max. angular velocity (°/s)	SD (°)
Walking	52.1	9.00	334	89.2
Stair ascent	87.4	11.7	351	59.6
Stair descent	77.3	9.43	313	61.3
Sit to stand	61.3	10.7	148	40.0
Stand to sit	62.0	12.3	149	59.7

‘SD’ equates to ‘Standard deviation’; ‘Max.’ to ‘Maximum’

Table 59 depicts the TE, STE, and PRESS error between the systems during walking, stair ascent, stair descent, sit to stand, and stand to sit.

Table 59 – Typical error (TE) and standardised typical error (STE) between the electrogoniometer and the motion analysis system during walking, stair ascent, stair descent, sit to stand, and stand to sit activities in ten asymptomatic participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	TE (°)	95% CI (°)		STE	95% CI		PRESS err. (°)
Walking	2.65	2.43	2.91	0.15	0.14	0.17	2.66
Max. knee flexion	3.02	2.55	3.48	0.25	0.13	0.42	3.03
Stair ascent	2.24	2.09	2.42	0.08	0.08	0.09	2.25
Max. knee flexion	2.96	2.65	3.40	0.27	0.17	0.39	2.91
Stair descent	1.93	1.79	2.10	0.08	0.08	0.09	1.94
Max. knee flexion	2.90	2.58	3.47	0.21	0.15	0.29	2.91
Sit to stand	1.30	1.22	1.41	0.06	0.05	0.06	1.31
Stand to sit	1.25	1.17	1.34	0.07	0.07	0.08	1.25

'SD' equates to 'Standard deviation'; 'CI' to 'Confidence interval'; 'err.' to 'Error'; 'Max.' to 'Maximum'

Level walking produced the greatest mean TE (2.65°; LCI=2.43°; UCI=2.91°) across the five activities over the total displacement cycles, although the magnitude of the STE was 'trivial' (<0.2) [157] (Table 59). The smallest TE over the total displacement cycle was observed in stand to sit (1.25°; LCI=1.17°; UCI=1.34°); with a 'trivial' STE (0.07; LCI=0.07; UCI=0.08) [157]. The PRESS error was greatest in level walking (2.66°), and smallest in stand to sit (1.25°) across the total displacement cycle.

Slightly greater errors were observed between systems at the point of maximum knee flexion. Walking produced an error of 3.02° (LCI=2.55°; UCI=3.48°), with stair ascent (2.96°; LCI=2.65°; UCI=3.40°) and stair descent (2.90°; LCI=2.58°; UCI=3.47°) indicative of comparable errors. Similarly, walking, stair ascent, and stair descent produced slightly greater errors when standardised than across the total displacement cycles, with 'small' STEs (0.2≤STE<0.6) [157]. Table 60 presents the linear relationship between systems across walking, stair ascent, stair descent, sit to stand, and stand to sit.

Table 60 – Pearson's correlation coefficient *r* depicting the linear relationship between the electrogoniometer and the motion analysis system during walking, stair ascent, stair descent, sit to stand, and stand to sit activities

	Pearson's correlation *r*	95% CI	
Walking	0.987	0.983	0.990
Max. knee flexion	0.980	0.930	0.999
Stair ascent	0.996	0.995	0.997
Max. knee flexion	0.971	0.965	0.978
Stair descent	0.996	0.995	0.997
Max. knee flexion	0.978	0.972	0.986
Sit to stand	0.998	0.998	0.999
Stand to sit	0.997	0.996	0.997

'SD' equates to 'Standard deviation'; 'CI' to 'Confidence interval'

Walking produced a mean Pearson's correlation coefficient *r* of 0.987 (LCI=0.983; UCI=0.990) over the total displacement cycle, which was the lowest correlation of the five activities. Stair ascent, stair descent, sit to stand, and stand to sit all produced correlations of >0.995 across the displacement cycles (Table 60).

Lower correlations were found at the point of maximum knee flexion across walking, stair ascent, and stair descent compared to the mean over the total displacement cycle. Stair ascent (0.971; LCI=0.965; UCI=0.978) and stair descent (0.978; LCI=0.972; UCI=0.986) derived the lowest correlations.

7.3.2 Experiment 2 – Reliability of knee kinematics and physical activity between-sessions

7.3.2.1 Angular displacement of the knee

Table 61 presents the results from the reliability assessment of the between-session angular displacement data.

Table 61 – Typical error (TE), standardised typical error (STE), and minimum detectable change (MDC) of the between-session right sagittal knee angular displacements over two eight hour ambulatory measurement periods between 8.00 am and 4.00 pm on two days in ten participants. Reliability was determined from the percentage of time spent within the 13 displacement categories. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥ 2 = very large [157]

Categories	TE (%)	95% CI (%)		STE	95% CI		MDC (%)
$-10° \leq \theta < 0°$	7.98	5.49	14.6	0.92	0.63	1.67	22.1
$0° \leq \theta < 10°$	7.95	5.47	14.5	0.78	0.54	1.43	22.0
$10° \leq \theta < 20°$	10.9	7.49	19.9	1.09	0.75	1.99	30.2
$20° \leq \theta < 30°$	3.80	2.61	6.93	0.69	0.48	1.26	10.5
$30° \leq \theta < 40°$	5.01	3.44	9.14	0.73	0.50	1.33	13.9
$40° \leq \theta < 50°$	9.26	6.37	16.9	1.02	0.70	1.87	25.7
$50° \leq \theta < 60°$	5.94	4.09	10.8	0.93	0.64	1.70	16.5
$60° \leq \theta < 70°$	15.1	10.4	27.5	1.06	0.73	1.94	41.7
$70° \leq \theta < 80°$	5.98	4.12	10.9	0.83	0.57	1.52	16.6
$80° \leq \theta < 90°$	3.92	2.70	7.16	0.70	0.48	1.28	10.9
$90° \leq \theta < 100°$	7.80	5.36	14.2	1.00	0.69	1.82	21.6
$100° \leq \theta < 110°$	6.08	4.18	11.1	1.02	0.70	1.86	16.9
$110° \leq \theta < 120°$	3.29	2.26	6.00	0.99	0.68	1.81	9.12
Mean	7.15	4.92	13.1	0.90	0.62	1.65	19.8
SD	3.26	2.24	5.96	0.14	0.10	0.26	9.04

‘θ’ equates to ‘Angular displacement’; ‘SD’ to ‘Standard deviation’; ‘CI’ to’ ‘Confidence interval’; ‘θ’ to ‘Angular displacement’

The greatest TEs between the two measurement periods were observed between $10° \leq \theta < 20°$ (10.9%) and $60° \leq \theta < 70°$ (15.1%) (Table 61). These errors were greatest when standardised, deriving ‘moderate’ STEs of 1.09 and 1.06 between $10° \leq \theta < 20°$ and $60° \leq \theta < 70°$, respectively [157]. The smallest TEs were observed between $20° \leq \theta < 30°$ (3.80%), $80° \leq \theta < 90°$ (3.92%), and $110° \leq \theta < 120°$ (3.29). The mean TE across all 13 categories was 6.47 ±3.81%. The standardisation of all 13 categories elicited STEs of 0.69 to 1.09 (mean=0.79 ±0.37) and classified as ‘moderate’ [157]. Table 62 presents Pearson’s correlation coefficient *r* and the ICC within categories and between measurement periods.

Table 62 – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) of the right sagittal knee angular displacements over two eight hour ambulatory measurement periods between 8.00 am and 4.00 pm on two days in ten participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

Categories	Pearson's correlation coefficient *r*	95% CI		ICC	95% CI	
-10° ≤ θ <0°	0.16	-0.52	0.72	0.18	-0.47	0.71
0° ≤ θ <10°	0.39	-0.32	0.82	0.43	-0.23	0.82
10° ≤ θ <20°	0.18	-0.73	0.50	-0.21	-0.72	0.45
20° ≤ θ <30°	0.53	-0.15	0.87	0.58	-0.04	0.87
30° ≤ θ <40°	0.47	-0.22	0.85	0.52	-0.11	0.86
40° ≤ θ <50°	-0.05	-0.66	0.60	-0.05	-0.64	0.57
50° ≤ θ <60°	0.14	-0.54	0.71	0.16	-0.49	0.69
60° ≤ θ <70°	-0.17	-0.72	0.52	-0.15	-0.69	0.50
70° ≤ θ <80°	0.32	-0.39	0.79	0.35	-0.32	0.79
80° ≤ θ <90°	0.52	-0.17	0.86	0.56	-0.06	0.87
90° ≤ θ <100°	0.01	-0.62	0.63	0.01	-0.60	0.61
100° ≤ θ <110°	-0.04	-0.66	0.60	-0.05	-0.63	0.57
110° ≤ θ <120°	0.02	-0.61	0.64	0.01	-0.59	0.61
Mean	0.19	-0.49	0.70	0.18	-0.43	0.69
SD	0.23	0.21	0.13	0.28	0.25	0.15

'θ' equates to 'Angular displacement'; 'SD' to 'Standard deviation'; 'CI' to 'Confidence interval';

Pearson's correlation coefficient *r* ranged from -0.17 (60°≤θ<70°) to 0.53 (20°≤θ<30°), deriving a mean of 0.19 ±0.23 (Table 62). Three categories displayed a negative correlation between the two testing periods, 40°≤θ<50° (-0.05), 60°≤θ<70° (-0.17), and 100°≤θ<110° (-0.04). The mean Pearson's correlation coefficient *r* of 0.19 ±0.23 was indicative of a 'small' positive effect between the two testing periods [113, 114]. Similar findings were observed in the ICC, with the analysis ranging from -0.21 (10°≤θ<20°) to 0.58 (20°≤θ<30°) and deriving a mean correlation of 0.18 ±0.28. Four of the 13 categories displayed negative correlations, 10°≤θ<20° (-0.21), 40°≤θ<50° (-0.05), 60°≤θ<70° (-0.15), and 100°≤θ<110° (-0.05). The mean ICC was indicative of 'poor' reliability (<0.50), with three groups (20°≤θ<30°; 30°≤θ<40°; 80°≤θ<90°) deriving 'moderate' reliability (0.5≤ICC<0.75) [172].

7.3.2.1 Angular velocity of the knee

Table 63 presents the results from the reliability assessment of the between-session angular velocity data.

Table 63 – Typical error (TE), standardised typical error (STE), and minimum detectable change (MDC) of the right sagittal knee angular velocities over two eight hour ambulatory measurement periods between 8.00 am and 4.00 pm on two days in ten participants. Reliability was determined from the percentage of time spent within the 14 velocity categories. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

Categories	TE (%)	95% CI (%)		STE	95% CI		MDC (%)
0°/s	2.48	1.70	4.52	1.01	0.70	1.85	6.87
0°/s ≤ ω <25°/s	5.61	3.86	10.3	0.90	0.62	1.65	15.6
25°/s ≤ ω <50°/s	5.78	3.98	10.6	1.00	0.69	1.82	16.0
50°/s ≤ ω <75°/s	3.27	2.25	5.98	0.91	0.63	1.67	9.06
75°/s ≤ ω <100°/s	2.73	1.88	4.99	1.04	0.72	1.91	7.57
100°/s ≤ ω <200°/s	4.03	2.77	7.36	1.02	0.70	1.86	11.2
200°/s ≤ ω <300°/s	2.09	1.44	3.82	0.89	0.61	1.62	5.79
300°/s ≤ ω <400°/s	0.94	0.64	1.71	0.79	0.54	1.44	2.61
400°/s ≤ ω <500°/s	0.90	0.62	1.64	0.92	0.63	1.68	2.49
500°/s ≤ ω <600°/s	0.57	0.39	1.03	0.91	0.62	1.66	1.58
600°/s ≤ ω <700°/s	0.40	0.27	0.72	0.89	0.61	1.62	1.11
700°/s ≤ ω <800°/s	0.31	0.22	0.57	0.94	0.64	1.71	0.86
800°/s ≤ ω <900°/s	0.30	0.21	0.55	0.94	0.64	1.71	0.83
900°/s ≤ ω <1000°/s	0.26	0.18	0.48	0.95	0.65	1.74	0.72
Mean	2.12	1.46	3.87	0.94	0.64	1.71	5.87
SD	1.95	1.34	3.56	0.07	0.05	0.12	5.40

'ω' equates to 'Angular velocity'; 'SD' to 'Standard deviation'; 'CI' to 'Confidence interval'

The greatest TE was observed between 25°/s≤ω<50°/s (5.78%) and when standardised produced a value of 1, which was less than the categories of 0°/s (1.01), 75°/s≤ω<100°/s (1.04), and 100°/s≤ω<200°/s (1.02) (Table 63). All STEs were considered of 'moderate' size [157]. The smallest TEs were observed in a consistent incremental reduction trend from 100°/s≤ω<200°/s to 900°/s≤ω<1000°/s. The mean TE across all categories was 2.12 ±1.95%, considerably lower than the mean angular displacement TE (6.47 ±3.81%). Table 64 outlines Pearson's correlation coefficient *r* and the ICC within categories and between the two measurement periods.

Table 64 – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) of the right sagittal knee angular velocities over two eight hour ambulatory measurement periods between 8.00 am and 4.00 pm on two days in ten participants. ICC<0.5 = poor; 0.5≤ICC< 0.75 = moderate; ICC≥0.75 = good [172]

Categories	Pearson's correlation coefficient *r*	95 % CI		ICC	95 % CI	
0°/s	-0.04	-0.65	0.60	-0.03	-0.62	0.58
0°/s ≤ ω <25°/s	0.28	-0.43	0.77	0.21	-0.45	0.72
25°/s ≤ ω <50°/s	0.01	-0.62	0.64	0.01	-0.60	0.61
50°/s ≤ ω <75°/s	0.29	-0.42	0.78	0.19	-0.47	0.71
75°/s ≤ ω <100°/s	-0.19	-0.73	0.50	-0.10	-0.66	0.53
100°/s ≤ ω <200°/s	-0.04	-0.65	0.60	-0.04	-0.63	0.58
200°/s ≤ ω <300°/s	0.21	-0.48	0.74	0.24	-0.42	0.74
300°/s ≤ ω <400°/s	0.40	-0.31	0.82	0.43	-0.23	0.82
400°/s ≤ ω <500°/s	0.15	-0.53	0.71	0.17	-0.48	0.70
500°/s ≤ ω <600°/s	0.18	-0.51	0.73	0.20	-0.46	0.72
600°/s ≤ ω <700°/s	0.22	-0.48	0.74	0.24	-0.42	0.74
700°/s ≤ ω <800°/s	0.13	-0.55	0.70	0.14	-0.50	0.69
800°/s ≤ ω <900°/s	0.14	-0.54	0.71	0.14	-0.50	0.69
900°/s ≤ ω <1000°/s	0.14	-0.54	0.71	0.11	-0.53	0.67
Mean	0.13	-0.53	0.70	0.14	-0.50	0.68
SD	0.16	0.11	0.09	0.14	0.11	0.08

'ω' equates to 'Angular velocity'; 'SD' to 'Standard deviation'; 'CI' to 'Confidence interval'

The Pearson's correlation coefficient *r* ranged from -0.19 (75°/s≤ω<100°/s) to 0.40 (300°/s≤ω<400°/s), with a mean of 0.13 ±0.16 indicative to a 'small' positive effect [113, 114] (Table 64). Three categories displayed a negative correlation, 0°/s (-0.04), 75°/s≤ω<100°/s (-0.19), and 100°/s≤ω<200°/s (-0.04). Similar findings were observed in the ICC, with the analysis ranging from -0.1 (75°/s≤ω<100°/s) to 0.43 (300°/s≤ω<400°/s), with a mean of 0.14 ±0.14. Three of the categories displayed negative correlations, 0°/s (-0.03), 75°/s≤ω<100°/s (-0.1), and 100°/s≤ω<200°/s (-0.04). The ICCs were indicative of 'poor' reliability [172].

7.3.2.3 Gross acceleration

Table 65 presents the results from the reliability assessment of the between-session angular velocity data.

Table 65 – Typical error (TE) and standardised typical error (STE) of the gross accelerations over two eight hour ambulatory measurement periods between 8.00 am and 4.00 pm on two days in ten participants. Reliability was determined from the percentage of time spent within the 14 velocity categories. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

Categories	TE (%)	95 % CI (%)		STE	95 % CI		MDC (%)
$0m/s^2$	6.12	4.13	11.7	0.92	0.62	1.76	17.0
$0m/s^2 \leq a < 0.25m/s^2$	2.92	1.97	5.60	0.55	0.37	1.05	8.09
$0.25m/s^2 \leq a < 0.5m/s^2$	0.67	0.45	1.28	0.63	0.42	1.20	1.86
$0.5m/s^2 \leq a < 0.75m/s^2$	0.73	0.49	1.40	0.74	0.50	1.42	2.02
$0.75m/s^2 \leq a < 1m/s^2$	0.89	0.60	1.71	0.74	0.50	1.41	2.47
$1m/s^2 \leq a < 1.25m/s^2$	1.48	1.00	2.83	0.70	0.47	1.35	4.10
$1.25m/s^2 \leq a < 1.5m/s^2$	3.10	2.10	5.94	1.00	0.68	1.92	8.59
$1.5m/s^2 \leq a < 1.75m/s^2$	0.11	0.07	0.21	0.49	0.33	0.94	0.30
$1.75m/s^2 \leq a < 2m/s^2$	0.16	0.11	0.31	1.05	0.71	2.00	0.44
$2m/s^2 \leq a < 2.25m/s^2$	0.09	0.06	0.17	1.06	0.72	2.04	0.25
$2.25m/s^2 \leq a < 2.5m/s^2$	0.13	0.09	0.25	1.03	0.70	1.98	0.36
$2.5m/s^2 \leq a < 2.75m/s^2$	0.12	0.08	0.23	1.02	0.69	1.95	0.33
$2.75m/s^2 \leq a < 3m/s^2$	2.22	1.50	4.25	1.00	0.68	1.92	6.15
Mean	1.44	0.97	2.76	0.84	0.57	1.61	4.00
SD	1.77	1.19	3.39	0.21	0.14	0.40	4.90

'a' equates to 'Acceleration'; 'SD' to 'Standard deviation'; 'CI' to 'Confidence interval'

The greatest TE exhibited was observed at $0m/s^2$ (6.12%), and when standardised, an error of 0.92 was produced, greater than the mean across all acceleration categories. Two categories, $0m/s^2 \leq a < 2.5m/s^2$ and $15m/s^2 \leq a < 17.5m/s^2$, derived STEs of 0.55 and 0.49, respectively, which were interpreted as 'small' [157]. The magnitude of the STE across the remaining 11 categories was 'moderate' [157]. Table 66 outlines Pearson's correlation coefficient *r* and the ICC within categories and between the two measurement periods.

Table 66 – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) of the gross accelerations over two eight hour ambulatory measurement periods between 8.00 am and 4.00 pm on two days in ten participants. ICC<0.5 = poor; 0.5≤ICC< 0.75 = moderate; ICC≥0.75 = good [172]

Categories	Pearson's correlation *r*	95 % CI		ICC	95 % CI	
$0 m/s^2$	0.18	-0.55	0.75	0.19	-0.51	0.73
$0 m/s^2 \le a < 0.25 m/s^2$	0.75	0.17	0.94	0.76	0.25	0.94
$0.25 m/s^2 \le a < 0.5 m/s^2$	0.62	-0.07	0.91	0.67	0.07	0.92
$0.5 m/s^2 \le a < 0.75 m/s^2$	0.50	-0.25	0.87	0.51	-0.18	0.86
$0.75 m/s^2 \le a < 1 m/s^2$	0.46	-0.30	0.86	0.52	-0.17	0.87
$1 m/s^2 \le a < 1.25 m/s^2$	0.53	-0.21	0.88	0.57	-0.10	0.88
$1.25 m/s^2 \le a < 1.5 m/s^2$	0.00	-0.67	0.66	0.00	-0.63	0.63
$1.5 m/s^2 \le a < 1.75 m/s^2$	0.82	0.35	0.96	0.82	0.38	0.96
$1.75 m/s^2 \le a < 2 m/s^2$	-0.14	-0.74	0.58	-0.11	-0.69	0.56
$2 m/s^2 \le a < 2.25 m/s^2$	-0.14	-0.73	0.58	-0.15	-0.72	0.53
$2.25 m/s^2 \le a < 2.5 m/s^2$	-0.23	-0.77	0.51	-0.08	-0.68	0.58
$2.5 m/s^2 \le a < 2.75 m/s^2$	-0.19	-0.76	0.54	-0.05	-0.66	0.60
$2.75 m/s^2 \le a < 3 m/s^2$	-0.19	-0.76	0.54	0.00	-0.63	0.63
Mean	0.23	-0.41	0.74	0.28	-0.33	0.75
SD	0.40	0.39	0.17	0.37	0.39	0.16

'a' equates to 'Acceleration'; 'SD' equates to 'standard deviation'; 'CI' to 'Confidence interval'

The Pearson's correlation coefficient *r* ranged from -0.23 ($2.25 m/s^2 \le a < 2.5 m/s^2$) to 0.82 ($1.5 m/s^2 \le a < 1.75 m/s^2$) across all 13 acceleration categories, deriving a mean of 0.23 ±0.4 (Table 66). The mean Pearson's correlation coefficient *r* of 0.23 ±0.4 was indicative of a 'small' positive effect between the two testing periods [113, 114]. Consistent findings were observed in the ICC, with the analysis ranging from -0.15 ($2 m/s^2 \le a < 2.5 m/s^2$) to 0.76 ($0 m/s^2 \le a < 0.25 m/s^2$) across all 13 acceleration categories, deriving a mean of 0.28 ±0.37. A mean weak positive correlation was derived (0.28 ±0.37) that was indicative of 'poor' reliability [172].

7.3.2.4 Number of steps undertaken

A TE of 2122 steps (LCI=1433; UCI=4065) was observed between the two measurement periods, deriving a 'moderate' STE (0.69; LCI=0.46; UCI=1.31) which was almost interpreted as 'small' [157] (0.2≤STE<0.6). The Pearson's correlation coefficient *r* was 0.65 (LCI=-0.03; UCI=0.92) which was indicative of a 'large' positive effect [113, 114]. An ICC of 0.59 (LCI=-0.06; UCI=0.89) was calculated, suggesting 'moderate' reliability [172]. A MDC of 5882 steps was calculated between-sessions.

7.3.3 Experiment 3 – Reliability of the electrogoniometry system

Table 67 depicts the TE and STE between-sessions across walking, stair ascent, stair descent, sit to stand, and stand to sit.

Table 67 – Typical error (TE), standardised typical error (STE), and minimum detectable change (MDC) of the sagittal right knee angular displacement measured by electrogoniometry during walking, stair ascent, stair descent, sit to stand, and stand to sit movements in ten participants between two sessions for the assessment of between-session reliability. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	TE (°)	95 % CI (°)		STE	95 % CI		MDC (°)
Walking	1.40	1.17	1.97	0.08	0.07	0.11	3.88
Max. knee flexion	2.04	1.68	2.45	0.14	0.09	0.19	5.65
Stair ascent	1.83	1.65	2.15	0.07	0.06	0.08	5.07
Max. knee flexion	2.25	1.97	2.56	0.19	0.14	0.26	6.24
Stair descent	1.60	1.45	1.85	0.07	0.06	0.08	4.43
Max. knee flexion	2.14	1.72	2.39	0.15	0.10	0.20	5.93
Sit to stand	0.94	0.86	1.09	0.04	0.04	0.05	2.61
Stand to sit	1.22	1.11	1.46	0.07	0.06	0.08	3.38

'SD' equates to 'Standard deviation'; 'CI' to 'Confidence interval'; 'Max.' to 'Maximum'

Stair ascent produced the greatest mean TE (1.83°; LCI=1.65°; UCI=2.15°) over the total displacement cycles between the two sessions (Table 67). Both sit to stand and stand to sit activities produced the smallest TEs (1.83°; LCI=1.65°; UCI=2.15° and 1.22°; LCI=1.11°; UCI=1.46°, respectively). Standardised TEs elicited 'trivial' values [157] between 0.04-0.08 across the total displacement cycles of the five ADLs. Greater errors were observed between-sessions at the point of maximum knee flexion, although the mean STEs were still deemed 'trivial' in magnitude [157]. Table 65 outlines Pearson's correlation coefficient *r* and the ICC between-sessions of walking, stair ascent, stair descent, sit to stand, and stand to sit for the measurement of the right sagittal knee angular displacement.

Table 68 – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) of right sagittal knee angular displacements as measured by electrogoniometry during walking, stair ascent, stair descent, sit to stand, and stand to sit movements in ten participants between two sessions for the assessment of between-session reliability. ICC<0.5 = poor; 0.5≤ICC< 0.75 = moderate; ICC≥0.75 = good [172]

	Pearson's correlation *r*	95% CI		ICC	95% CI	
Walking	0.990	0.968	0.995	0.990	0.984	0.995
Max. knee flexion	0.951	0.910	0.981	0.947	0.909	0.978
Stair ascent	0.980	0.910	0.992	0.992	0.990	0.994
Max. knee flexion	0.940	0.903	0.985	0.941	0.910	0.983
Stair descent	0.984	0.930	0.994	0.993	0.991	0.995
Max. knee flexion	0.941	0.911	0.979	0.944	0.906	0.976
Sit to stand	0.996	0.984	0.998	0.997	0.996	0.997
Stand to sit	0.992	0.970	0.996	0.993	0.991	0.994

'CI' to 'Confidence interval'

The greatest mean Pearson correlation coefficient *r* over the total displacement cycles were observed in sit to stand (0.996; LCI=0.984; UCI=0.998) and stand to sit (0.992; LCI=0.970; UCI=0.996) (Table 68). Stair ascent (0.998; LCI=0.910; UCI=0.992) and stair descent (0.984; LCI=0.930; UCI=0.994) derived the smallest mean Pearson correlation coefficient *r* over the total displacement cycles. Consistent findings were observed in the ICCs, with magnitudes of >0.99 across all activities over the total displacement cycles that were indicative of 'good' reliability [172].

Lower correlations were found at the point of maximum knee flexion across walking, stair ascent, and stair descent compared to the mean over the total displacement cycle. Stair ascent and stair descent derived the lowest correlations (≤0.930). Similar findings were observed in the ICCs, with slightly lower magnitudes at maximum knee flexion than across the total displacement cycles, but still indicative of 'good' reliability [172].

7.4 Discussion

The electrogoniometer was concurrently validated in Experiment 1 against a three dimensional motion analysis system which is a technique deemed accurate [272], capable of measuring knee biomechanics to a high degree of precision [73], and has been described as the "gold standard" for knee kinematic measurement [72]. The derived TE ranged from 1.25° (LCI=1.17°; UCI=1.34°) during stand to sit, to 2.65° (LCI=2.43°; UCI=2.91°) during walking across the total displacement cycle. The magnitude of error in this investigation was comparable to that of previous studies analysing walking [72, 136], although the authors reported mean differences and not TE, making any direct comparisons problematic. Authors have previously reported the TE between an electrogoniometer and three dimensional motion analysis system, with Bronner et al. [273] assessing dancing movements in advanced level collegiate dancers. The authors reported differences up to 6.80°, a magnitude considerably greater than the error observed at maximum knee flexion during walking in the current study (3.02°; LCI=2.55°; UCI=3.48°). These greater errors were likely to be caused by the dancing movements assessed as these are often performed at joint extremes [273], and are therefore more likely to assume greater magnitudes of displacement and velocity than those reached during ADLs.

In the current study, errors at maximum knee flexion were found to be greater than the mean error across the total displacement cycle during walking, stair ascent, and stair descent. Electrogoniometry has been previously found to display reduced accuracy approaching motion extremes at the wrist [274] and during laboratory investigation [275]. In these situations, crosstalk has been determined to be an important contributing factor to producing error [274, 275]. As only sagittal plane displacements were measured in the current study, potential crosstalk errors were eliminated. Soft tissue artefact (STA) errors, therefore, may have accounted for the greater differences observed at increased magnitudes of flexion. The proximal and distal endplates of the electrogoniometer were attached directly onto the skin over the lateral aspect of the thigh and shank, respectively. Underlying soft tissues interposed between the skin and the bone are typically exposed to inertial movements caused by elastic and damping components, in addition to changes in shape due to muscular activity during ambulation. This unstable geometry may have exacerbated differences between systems to the order of magnitude observed, although, no substantial differences in error were observed between the more muscular demanding tasks of stair ascent (2.96°; LCI=2.65°; UCI=3.40°) and stair descent (2.90°; LCI=2.58°; UCI=3.47°) when compared to walking (3.02°; LCI=2.55°; UCI=3.48°).

Rowe et al. [72] documented small errors at maximum knee flexion with a mean of 0.9° between systems. A potential contributor to reduced error in Rowe et al. [72] was the endplates of the electrogoniometer were mounted upon plastic strips to avoid direct instrument to skin contact. Equalising foam blocks were also used to reduce the abduction and adduction angulation at the knee in order to allow instrument attachment on a level surface. In the current study, mounting of the electrogoniometer directly onto the skin was undertaken with a view to following manufacturer guidelines [133], in addition to examining the validity of an attachment procedure that could be used with minimal additional instrumentation and therefore more suited to applied clinical use. Further, the use of foam blocks in the current study would have created a magnitude of lateral protrusion, thus increasing the risk of instrument displacement during free living conditions due to potential contact with external objects. Due to these reasons, this method was not pursued. Despite the findings of Rowe et al. [72], Indramohan et al. [264] found that their results were unaffected when attaching the electrogoniometer directly onto the skin in a study validating a data logger for use with electrogoniometers. The results of the current study, Rowe et al. [72], and Indramohan et al. [264] suggest that reasonable errors can be derived regardless of attachment method.

The mean linear relationship between systems, from which the TE was derived, was found to be very high across the total displacement cycles of walking, stair ascent, stair descent, sit to stand, and stand to sit, ranging from 0.987 in walking to 0.998 during sit to stand. In previous work, Bronner et al. [273] detailed a comparable, but reduced overall magnitude of correlation (≥0.949) to the findings of the current study. These reductions were likely to be caused by the previously discussed differences in activities between the current study and Bronner et al. [273]

The findings of Experiment 1 suggest that accurate data can be obtained with direct instrument to skin attachment, although these errors can increase at greater magnitudes of knee flexion. Increased angular velocity may also contribute to greater error [273], as walking, stair ascent, and stair descent were indicative of considerably greater angular velocity than sit to stand and stand to sit movements, whilst also deriving greater errors. The results of the current study can be considered valid to one standard deviation (SD) up to angles of 99.06° and angular velocities of 423.62°/s.

Experiment 2 was undertaken to determine the between-session reliability and MDC of the electrogoniometry system when combined with a previously validated accelerometry system for quantifying gross physical activity and the number of steps undertaken [276], with a view to measuring both knee kinematics and physical activity during free living conditions. Initial pilot tests determined that measurement over a 24 hour period was logically possible; however, the mean battery life was found to be 8.46 ±0.036hours during continuous measurement at the lowest programmable sampling rate of 200Hz, similar to the recognised limitations of previous reports [146, 268]. It was proposed to abstain from utilising external power packs as the additional size and mass could have inhibited normal physical activity during measurement. As a result, a measurement interval of eight hours was selected to be within the lower SD limit of the battery life. The use of an eight hour interval has been previously undertaken in the application of electrogoniometry to measure sagittal knee kinematics of patients following TKR [146], supporting its use in the current study.

Standardised TEs that were ‘moderate’ [157] in magnitude were derived across the angular displacement categories between the two eight hour measurement periods. Similar ‘moderate’ [157] magnitudes were observed across the angular velocity, gross acceleration, and step count categories. The Pearson’s *r* and ICCs were indicative of poor reliability across the angular displacement, velocity, and gross acceleration categories, with moderate reliability in the number of steps undertaken between-sessions. A limitation of the Pearson’s *r* correlation coefficient is that the statistic only provides an indication of the linear relationship between trials, and therefore does not account for potential non-linear relationships. Further limitations include the inability of the statistic to contextualise error, where seemingly good correlations can potentially conceal substantial errors. Similar issues are evident withthe utility of the ICC as a reliability measure. Limitations include its dependence on the range of the measurement, and it is therefore not related to the actual scale of measurement or to the size of error [277]. Low ICC magnitudes can be subsequently derived because the variability between participants is low, and not because the trials exhibit poor agreement [152, 168, 277].

These limitations support the use of error as the primary determinant in the assessment of reliability; however despite these limitations, when combined with the error the results suggest that between-session sagittal knee kinematics and gross physical activity were moderately variable. The reliability of ActiGraph accelerometers have been previously defined and confirmed [140, 148, 278], suggesting that the findings of the current study represent true between-session differences in gross physical activity. What is more unclear, based on current evidence, is the interpretation of the knee kinematic magnitude of error as few authors have provided data on the reliability of knee kinematics between-sessions during ADLs [134, 152]. Authors have assessed the reliability of electrogoniometry during both static [134] and dynamic conditions [148], however, different attachment procedures and data logging systems have been utilised that limit the cross application of findings. As a result, Experiment 3 was performed to define the between-session reliability of the electrogoniometry system in the laboratory over controlled ADLs. This was required in order to accurately infer whether the differences observed in Experiment 2 could be attributed to true differences in knee kinematics between-sessions, or to poor reliability of the electrogoniometry system.

The results of Experiment 3 demonstrated ‘small’ errors [157] indicative of good reliability across the total displacement cycles of all activities. Data were analysed at maximum knee flexion during walking, stair ascent, and stair descent due to the post-hoc findings of Experiment 1. Despite showing slightly increased error, the magnitude was still interpreted as ‘small’ [157], with the ICCs indicative of ‘good’ reliability [172]. These data give an indication to the contribution of electrogoniometry system error to the between-session error detailed in Experiment 2. Maximum knee flexion during stair ascent exhibited a MDC of 6.24°, the largest across all activities. A difference up to 6.24° can therefore be expected between-sessions during free living conditions at greater magnitudes of knee flexion (~87°) when controlling knee kinematic differences, with this error inclusive of within-session movement cycle variation from trial to trial and instrument attachment inconsistencies between-sessions. Between-session MDC results in Chapter 4 exhibited magnitudes up to 6.25° in sagittal knee ROM during stair ascent in controls (Table 34), similar to the finding of 6.24° obtained in the current study. This suggests the results of the current study using electrogoniometry are representative of those obtained using a three dimensional motion analysis system.

Despite the findings of overall 'moderate' errors [157] and 'poor' to 'moderate' correlations [113, 172] in Experiment 2, the MDC was calculated in order to inform differences in the application of the systems to compare FB and MB patients in Chapter 8. The MDC in this instance allows valid interpretations of potential between-group differences in knee kinematics and physical activity within the defined error limits, supporting the continued use of the systems for clinical applications. As the electrogoniometry system was determined to be both valid and reliable over specific movement cycles in the laboratory (Experiment 1 and 3), any differences found in Chapter 8 could be attributed to changes in knee kinematics between FB and MB groups.

7.4.1 Limitations

A limitation of this study is that it may be problematic when extrapolating these results from a relatively young, asymptomatic cohort to TKR patients. The findings of Chapters 5 and 6 showed that the TKR cohort typically ambulated with reduced velocity and sagittal knee ROM compared to controls. These differences are likely to be exacerbated when compared to this study, as a younger cohort of controls were tested. This suggests that the electrogoniometry system may exhibit greater validity in the TKR population than presented in Experiment 1 of this study, as greater sagittal knee ROM and velocity have been associated with reduced validity from the findings of Experiment 1 and Bronner et al. [273]. In contrast, the findings of van der Linden et al. [152] suggest potentially reduced reliability in OA and TKR patients, although this was still found to be good. Methodological issues such as not standardising the footwear that patients wore, may have also contributed to the reduced reliability in van der Linden et al. [152], rather than the isolated effect of increased age and symptomatic burden.

The undertaking of only two measurement periods in Experiment 2 may have contributed to the 'moderate' error [157] observed between sessions. The reliability of measurements has been found to increase with the inclusion of more trials, with fewer trials reducing the reliability [176-179]. Two measurement periods were undertaken in the current study as only one period was planned in the testing of FB and MB groups in Chapter 8 due to the availability of only one system, therefore, only one patient could be measured at one time. In addition, patients were typically recruited at pre-surgery assessment clinics, often within a week of their surgery date. This left little time to undertake multiple testing periods over multiple days, with the experimentation presented in Chapters 5 and 6 also required in the pre-surgery window. Patients on waiting lists were also offered advanced dates in the event of surgical cancellations, therefore, testing both in the gait laboratory and during free living conditions needed to be performed at short notice, often within a few days prior to surgery. As only one trial was performed in Chapter 8, the use of two trials in this study provides an exaggerated approximation of the error.

7.5 Conclusions

- The electrogoniometry system appeared to be a valid measure of sagittal knee kinematics compared to three dimensional motion analysis during ADLs, although validity was reduced at greater magnitudes of knee flexion and velocity.
- Between-session knee kinematics and physical activity during free living conditions derived moderate errors. The electrogoniometry system was, however, deemed indicative of good reliability during specific activities in the laboratory.
- MDC values were calculated to allow valid interpretations of potential between-group differences in sagittal knee kinematics and physical activity within the defined error limits in Chapter 8.

8.0 Knee kinematics and physical activity of fixed bearing and mobile bearing total knee replacement patients during free living conditions away from the laboratory

8.1 Introduction

Chapter 7 of this thesis introduced an objective method of using electrogoniometry and accelerometry to measure the sagittal knee kinematics and physical activity of participants during free living conditions away from the laboratory. Technological advances in hardware miniaturisation, data storage, and software optimisation mean that these sensors can be worn unobtrusively without affecting the daily physical activity patterns of the participants being measured [263], thus providing a method of behaviour monitoring [279]. The use of electrogoniometry and accelerometry provide an alternative to three dimensional motion analysis in certain clinical situations, as the high cost, requirement for specialist staff, and the requirement for a specialist laboratory make the method less than ideal for routine clinical assessments [184]. Due to these reasons, the current success of total knee replacement (TKR) procedures are often assessed using patient self-report questionnaires which may not accurately reflect the true capabilities of the patient [146].

The use of electrogoniometry in orthopaedic research is growing [72, 152, 153, 184, 190, 265, 266], although few authors have used electrogoniometers to measure sagittal knee kinematics of patients during free living conditions [82, 146, 268]. D’Lima et al. [82] developed an instrumented tibial prosthetic design using load cells and a telemetry system. The authors utilised a custom electrogoniometer to measure sagittal knee kinematics, and described a mean error of 6° when compared to sagittal knee kinematics measured using fluoroscopy. Only validation data were presented, with no data relating to knee kinematics during unsupervised activities away from observation, although the authors stated that current work was on-going.

Both Morlock et al. [268] and Cavanagh et al. [146] have presented sagittal knee kinematic data over six hours and eight hours, respectively. Morlock et al. [268] determined the duration and frequency of ADLs in patients following total hip replacement surgery. The most frequent activity was sitting (44.3% of the time), followed by standing (24.5%), walking (10.2%), lying (5.8%), and stair negotiation (0.4%). In a preliminary abstract, Cavanagh et al. [146] presented a system for remote kinematic monitoring and activity recognition in patients following TKR. The authors detailed 1492 joint motions above a 10° threshold during the measurement period, with 33 (2.21%) of these >40°. Despite these initial analyses, no research has been undertaken in the comparison of fixed bearing (FB) or mobile bearing (MB) total knee prostheses. The accurate knowledge of knee kinematics is valuable for the understanding of implant design [280]. Due to the findings of Kurtz et al. [3], this becomes more prominent due to a changing demographic of TKR patients that require optimised prosthesis function adapted to the higher physical demands of the younger patient.

The aim of this chapter was to measure sagittal knee angular displacement, sagittal knee angular velocity, and physical activity during eight hours of measurement during free living conditions away from the laboratory in the comparison of FB and MB groups. This was undertaken to further investigate the hypothetical benefits of the MB prosthesis. Although no differences in laboratory testing were found in Chapters 5 and 6, it is currently unknown whether the axial rotation of the MB prosthesis results in the patients flexing their knee at greater degrees of flexion over longer periods of time. It is also unknown what the expected spectrum of sagittal knee angular displacement and velocity is at the knee regardless of prosthetic design, during free living conditions.

8.2 Method

8.2.1 A priori power calculation

The power calculation at the investigation outset was described in Chapter 5 (‘5.2.1 A priori power calculation’).

8.2.2 Participants

The patient cohort that was described in Chapter 4 ('4.2.1 Participants') was used in this study. The control cohort that was described in Chapter 7 ('7.2.1 Participants') was used for comparison.

8.2.3 Instrumentation set-up and protocol

The instrumentation set-up of the electrogoniometry and accelerometry systems was described in Chapter 3 ('3.3.1 Ambulatory protocol used in the electrogoniometry and accelerometry systems for testing away from the laboratory'). Patients were visited at their home at 7.40am on the day of testing, with testing beginning at a standardised time of 8.00am. The electrogoniometry and accelerometry systems captured data for eight hours, with the author returning to the patient's home at 4.00pm for instrument removal.

8.2.4 Data analysis

Data cleaning and processing in the electrogoniometry and accelerometry systems were undertaken in line with the methods described in Chapter 3 ('3.3.2 Data cleaning and processing in the in the electrogoniometry and accelerometry systems'). All statistical analyses were undertaken in line with the methods described in Chapter 5 ('5.2.4 Data analysis').

8.3 Results

8.3.1 Angular displacement spectrum

Pairwise comparisons are presented in Table 69 relating to the differences between FB, MB, and control groups in the sagittal knee angular displacement spectrum at pre-surgery.

Table 69 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the sagittal knee angular displacement spectrum at the pre-surgery time point during eight hours of measurement away from the laboratory during free living conditions

Pre-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
$-10° \leq \theta < 0°$	2.38	2.90	8.72	10.8	7.23	6.90	$p = 0.76$	0.20	-	-	-
$0° \leq \theta < 10°$	15.9	21.2	22.1	11.6	13.9	8.88	$p = 0.31$	1.21	-	-	-
$10° \leq \theta < 20°$	11.1	14.4	13.5	11.7	11.5	6.49	$p = 0.36$	1.06	-	-	-
$20° \leq \theta < 30°$	9.41	10.9	8.51	8.31	7.95	5.20	$p = 0.32$	1.20	-	-	-
$30° \leq \theta < 40°$	10.0	7.65	7.72	6.94	8.24	6.44	$p = 0.62$	0.48	-	-	-
$40° \leq \theta < 50°$	12.7	12.4	13.4	15.8	9.46	6.64	$p = 0.83$	0.19	-	-	-
$50° \leq \theta < 60°$	9.03	4.97	5.83	4.69	7.30	5.39	$p = 0.43$	0.76	-	-	-
$60° \leq \theta < 70°$	3.85	2.26	7.76	8.56	10.6	10.5	$p = 0.19$	1.75	-	-	-
$70° \leq \theta < 80°$	5.15	3.64	7.77	6.51	5.41	3.18	$p = 0.22$	1.59	-	-	-
$80° \leq \theta < 90°$	8.54	5.61	2.67	2.30	4.99	3.62	$p = 0.95$	0.05	-	-	-
$90° \leq \theta < 100°$	6.96	6.58	1.61	2.44	7.49	5.68	$p = 0.10$	2.43	-	-	-
$100° \leq \theta < 110°$	2.90	3.00	0.45	0.80	4.91	4.35	$\boldsymbol{p < 0.05}$	4.59	0.96	*****	0.71
$110° \leq \theta < 120°$	2.06	2.61	0.00	0.01	1.78	2.53	$\boldsymbol{p < 0.05}$	5.17	1.00	0.32	0.37

'θ' equates to 'Angular displacement'; 'SD' to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*' to 'Significant at the 0.05 level'

All groups spent the greatest percentage of time with the knee flexed between 0°≤θ<10° (FB=15.9 ±21.2%; MB=22.1 ±11.6%; control=3.88 ±8.88%) (Table 69). When two angular displacement categories were combined to create a 20° increment, all groups exhibited the greatest percentage of time between 0°≤θ<20° (FB=27.0%; MB=35.6%; control=25.4%). Despite not reaching significance, the FB group displayed a greater mean duration of the eight hour measurement period with the knee flexed >100° (4.96%) than when compared to the MB group (0.45%), although this was reduced in relation to the control group (6.88%). Only one angular displacement category reached significance (p<0.05) at pre-surgery, with the MB group spending a reduced percentage of time with the knee flexed between 100°≤θ<110° than the control group ($F_{2,32}$ = 4.59; p<0.05). A similar pattern was observed between FB and MB groups with a maximum percentage magnitude between 0°≤θ<10° (FB=15.9 ±21.2%; MB=22.1 ±11.6%) and a smaller, but apparent, second peak between 40°≤θ<50° (FB=12.7 ±12.4%; MB=13.4 ±15.8%). No differences were observed between FB and MB groups. Pairwise comparisons are presented in Table 70 relating to the differences between FB, MB, and control groups in the sagittal knee angular displacement spectrum at three months post-surgery.

Table 70 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the sagittal knee angular displacement spectrum at the three months post-surgery time point during eight hours of measurement away from the laboratory during free living conditions

Three months post-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
-10°≤ θ <0°	0.18	0.35	6.51	13.7	7.23	6.90	$p = 0.76$	0.20	-	-	-
0°≤ θ <10°	11.2	22.2	15.7	18.1	13.9	8.88	$p = 0.31$	1.21	-	-	-
10°≤ θ <20°	12.1	7.61	20.1	13.1	11.5	6.49	$p = 0.36$	1.06	-	-	-
20°≤ θ <30°	16.3	8.21	11.2	7.93	7.95	5.20	$p = 0.32$	1.20	-	-	-
30°≤ θ <40°	7.32	4.95	7.39	6.44	8.24	6.44	$p = 0.62$	0.48	-	-	-
40°≤ θ <50°	14.2	15.1	14.4	17.2	9.46	6.64	$p = 0.83$	0.19	-	-	-
50°≤ θ <60°	17.3	7.18	6.85	6.15	7.30	5.39	$p = 0.43$	0.76	-	-	-
60°≤ θ <70°	4.80	5.46	9.57	6.42	10.6	10.5	$p = 0.19$	1.75	-	-	-
70°≤ θ <80°	11.5	15.7	13.4	10.3	5.41	3.18	$p = 0.22$	1.59	-	-	-
80°≤ θ <90°	4.03	5.10	6.91	8.12	4.99	3.62	$p = 0.95$	0.05	-	-	-
90°≤ θ <100°	1.07	2.15	1.71	4.30	7.49	5.68	$p = 0.10$	2.43	-	-	-
100°≤ θ <110°	0.00	0.00	0.56	1.48	4.91	4.35	$\boldsymbol{p < 0.05}$	4.59	0.05	*****	1.00
110°≤ θ <120°	0.00	0.00	0.00	0.00	1.78	2.53	$\boldsymbol{p < 0.05}$	5.17	0.30	0.17	1.00

‘θ’ equates to ‘Angular displacement’; ‘SD’ to ‘Standard deviation’; ‘Sig.’ to ‘Significance of ANOVA’; ‘F’ to ‘F statistic’; ‘*’ to ‘Significant at the 0.05 level’

The greatest percentage of time observed within a ten degree incremental category was different between groups (Table 70). The FB group displayed the greatest percentage of time with the knee flexed between $50° \leq \theta < 60°$ (17.3 ±7.18%), with the MB group between $10° \leq \theta < 20°$ (20.1 ±13.1%). Differences were apparent when categories were combined to create a 20° increment, with the FB group exhibiting the greatest duration of time with the knee flexed between $40° \leq \theta < 60°$ (31.5%) and the MB group between $0° \leq \theta < 20°$ (35.8%). Both FB and MB groups displayed few knee angular displacements >100° (FB=0.00%; MB=0.56%). Differences between groups were observed between $100° \leq \theta < 110°$, with the MB group (0.56 ±1.48%) found to spend a reduced percentage of time with the knee flexed between $100° \leq \theta < 110°$ than the control group (4.91 ±4.35%) ($F_{2,32} = 4.59$; $p<0.05$). Pairwise comparisons are presented in Table 71 relating to the differences between FB, MB, and control groups in the sagittal knee angular displacement spectrum at nine months post-surgery.

Table 71 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the sagittal knee angular displacement spectrum at the nine months post-surgery time point during eight hours of measurement away from the laboratory during free living conditions

Nine months post-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
-10°≤ θ <0°	10.0	5.88	6.19	8.26	7.23	6.90	$p = 0.76$	0.20	-	-	-
0°≤ θ <10°	12.0	8.90	12.9	17.5	13.9	8.88	$p = 0.31$	1.21	-	-	-
10°≤ θ <20°	8.28	7.50	13.9	10.1	11.5	6.49	$p = 0.36$	1.06	-	-	-
20°≤ θ <30°	18.4	13.1	10.2	7.45	7.95	5.20	$p = 0.32$	1.20	-	-	-
30°≤ θ <40°	22.7	15.5	10.9	13.1	8.24	6.44	$p = 0.62$	0.48	-	-	-
40°≤ θ <50°	8.84	2.10	12.5	10.5	9.46	6.64	$p = 0.83$	0.19	-	-	-
50°≤ θ <60°	11.4	16.1	8.40	12.1	7.30	5.39	$p = 0.43$	0.76	-	-	-
60°≤ θ <70°	6.89	12.4	6.18	4.94	10.6	10.5	$p = 0.19$	1.75	-	-	-
70°≤ θ <80°	1.49	2.94	8.04	8.13	5.41	3.18	$p = 0.22$	1.59	-	-	-
80°≤ θ <90°	0.00	0.00	4.58	5.35	4.99	3.62	$p = 0.95$	0.05	-	-	-
90°≤ θ <100°	0.00	0.00	4.25	8.78	7.49	5.68	$p = 0.10$	2.43	-	-	-
100°≤ θ <110°	0.00	0.00	1.89	4.79	4.91	4.35	$\boldsymbol{p < 0.05}$	4.59	0.21	0.52	1.00
110°≤ θ <120°	0.00	0.00	0.08	0.21	1.78	2.53	$\boldsymbol{p < 0.05}$	5.17	0.31	0.20	1.00

‘θ’ equates to ‘Angular displacement’; ‘SD’ to ‘Standard deviation’; ‘Sig.’ to ‘Significance of ANOVA’; ‘F’ to ‘F statistic’; ‘*’ to ‘Significant at the 0.05 level’

No consistency between groups was observed with regards to the greatest percentage of time spent within a ten degree incremental category of knee flexion (Table 71). The FB group displayed a magnitude of 22.7 ±15.5% between $30° \leq \theta < 40°$, with the MB group a magnitude of 13.9 ±10.1% between $10° \leq \theta < 20°$. Differences were also apparent when categories were combined to create a 20° increment, with the FB group displaying 41.1% of all knee angular displacements between $20° \leq \theta < 40°$, and the MB group deriving a magnitude of 26.8% between $0° \leq \theta < 20°$. Fixed bearing patients displayed no knee angular displacements >80°. No significant differences were observed between groups across all incremental categories. The combined between-group results of the sagittal knee angular displacement spectrum across FB, MB, and control groups at pre-surgery, three months post-surgery, and nine months post-surgery are graphically depicted in Figure 15.

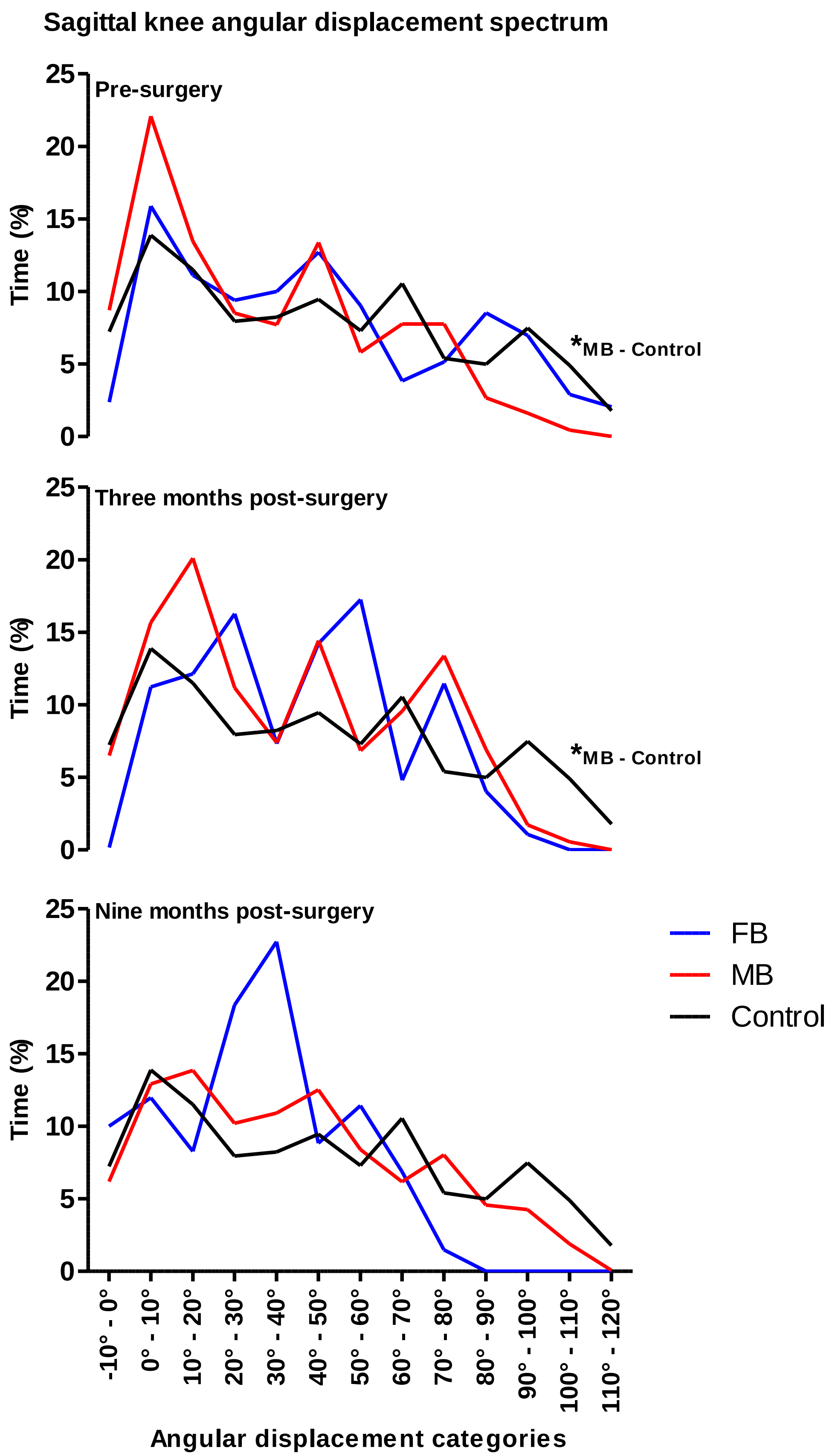

Figure 15 – Sagittal knee angular displacement spectrum of fixed bearing (FB), mobile bearing (MB), and control participants at pre-surgery, three months post-surgery, and nine months post-surgery during eight hours of ambulatory measurement between 8.00 am and 4.00 pm. Significant between group differences (p<0.05) are depicted by the asterisks (*)

Table 72 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the sagittal knee angular displacement spectrum.

Table 72 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of sagittal knee angular displacements in fixed bearing (FB) and mobile bearing (MB) patients during eight hours of measurement away from the laboratory during free living conditions

		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	-10°≤ θ <0°	$p = 0.42$	0.79	-	-	-
	0°≤ θ <10°	$p = 0.49$	0.74	-	-	-
	10°≤ θ <20°	$p = 0.57$	0.57	-	-	-
	20°≤ θ <30°	$p = 0.29$	1.29	-	-	-
	30°≤ θ <40°	**$p < 0.05$**	6.18	1.00	*	*
	40°≤ θ <50°	$p = 0.83$	0.19	-	-	-
	50°≤ θ <60°	$p = 0.39$	0.89	-	-	-
	60°≤ θ <70°	$p = 0.88$	0.13	-	-	-
	70°≤ θ <80°	$p = 0.07$	3.38	-	-	-
	80°≤ θ <90°	$p = 0.07$	2.92	-	-	-
	90°≤ θ <100°	$p = 0.33$	1.13	-	-	-
	100°≤ θ <110°	$p = 0.38$	0.92	-	-	-
	110°≤ θ <120°	**$p < 0.05$**	6.11	*	1.00	*
MB	-10°≤ θ <0°	$p = 0.42$	0.79	-	-	-
	0°≤ θ <10°	$p = 0.49$	0.74	-	-	-
	10°≤ θ <20°	$p = 0.57$	0.57	-	-	-
	20°≤ θ <30°	$p = 0.29$	1.29	-	-	-
	30°≤ θ <40°	**$p < 0.05$**	6.18	1.00	0.91	1.00
	40°≤ θ <50°	$p = 0.83$	0.19	-	-	-
	50°≤ θ <60°	$p = 0.39$	0.89	-	-	-
	60°≤ θ <70°	$p = 0.88$	0.13	-	-	-
	70°≤ θ <80°	$p = 0.07$	3.38	-	-	-
	80°≤ θ <90°	$p = 0.07$	2.92	-	-	-
	90°≤ θ <100°	$p = 0.33$	1.13	-	-	-
	100°≤ θ <110°	$p = 0.38$	0.92	-	-	-
	110°≤ θ <120°	**$p < 0.05$**	6.11	1.00	0.37	1.00

'θ' equates to 'Angular displacement'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*' to 'Significant at the 0.05 level'; 'PS' to 'Post-surgery'

Only the FB group reached significance in the pairwise comparisons (Table 72). Reductions were found from pre-surgery to three months post-surgery in the magnitude of time spent with the knee flexed between 110°≤θ<120° ($F_{1.02,16.3} = 6.11$; $p<0.05$). From three months post-surgery to nine months post-surgery, there was an increase in the amount of time spent with the knee flexed between 30°≤θ<40° in the FB group ($F_{2,32} = 6.18$; $p<0.05$).

8.3.2 Angular velocity spectrum

Pairwise comparisons are presented in Table 73 relating to the differences between FB, MB, and control groups in the sagittal knee angular velocity spectrum at pre-surgery.

Table 73 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the sagittal knee angular velocity spectrum at the pre-surgery time point during eight hours of measurement away from the laboratory during free living conditions

Pre-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
0°/s	8.32	0.50	8.18	1.61	8.88	1.91	$p = 0.05$	3.74	-	-	-
0°/s≤ ω <25°/s	22.7	2.93	24.4	2.21	21.9	5.28	$p = 0.73$	0.31	-	-	-
25°/s≤ ω <50°/s	20.9	2.29	22.3	2.27	21.5	4.64	$p = 0.24$	1.50	-	-	-
50°/s≤ ω <75°/s	14.7	1.23	15.6	0.83	14.6	3.07	$p = 0.70$	0.36	-	-	-
75°/s≤ ω <100°/s	11.0	0.72	11.4	0.54	12.0	1.98	$p = 0.06$	3.99	-	-	-
100°/s≤ ω <200°/s	14.8	2.07	13.5	3.59	17.3	2.47	$p = 0.16$	1.97	-	-	-
200°/s≤ ω <300°/s	3.82	2.14	3.06	1.91	5.33	1.61	$p = 0.30$	1.27	-	-	-
300°/s≤ ω <400°/s	1.58	1.05	0.92	0.71	2.33	0.98	$\boldsymbol{p < 0.05}$	4.70	0.59	*****	0.86
400°/s≤ ω <500°/s	0.90	0.65	0.34	0.39	1.25	0.81	$\boldsymbol{p < 0.05}$	6.63	1.00	0.07	0.65
500°/s≤ ω <600°/s	0.48	0.35	0.13	0.22	0.51	0.54	$\boldsymbol{p < 0.05}$	3.46	1.00	0.34	0.66
600°/s≤ ω <700°/s	0.36	0.29	0.09	0.17	0.27	0.38	$p = 0.27$	1.38	-	-	-
700°/s≤ ω <800°/s	0.23	0.20	0.05	0.10	0.15	0.25	$p = 0.40$	0.95	-	-	-
800°/s≤ ω <900°/s	0.22	0.20	0.03	0.08	0.13	0.22	$p = 0.36$	1.05	-	-	-
900°/s≤ ω <1000°/s	0.16	0.17	0.02	0.05	0.09	0.17	$p = 0.30$	1.22	-	-	-

'ω' equates to 'Angular velocity'; 'SD' to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*' to 'Significant at the 0.05 level'

At pre-surgery, all groups spent the greatest percentage of time with the knee displacing between 0°/s≤ω<25°/s (FB=22.7 ±2.93%; MB=24.4 ±2.21%; control=21.9 ±5.28%) (Table 73). A similar percentage of time between groups was also observed with the knee angle remaining constant, an angular velocity of 0°/s (FB=8.32 ±0.50%; MB=8.18 ±1.61%; control=8.88 ±1.91%). A reduction across all groups was apparent in the percentage of time spent with the knee displacing ≥200°/s, with only 7.75% and 4.63% in the FB and MB groups, respectively, greater than this threshold (control=10.1%). Significance in the pairwise comparisons was reached in one category, with the MB group spending a reduced ($F_{2,32}$ = 4.70; p<0.05) magnitude of time with the knee displacing between 300°/s≤ω<400°/s (0.92 ±0.71%) than controls (2.33 ±0.98%). No differences were observed between FB and MB groups. Pairwise comparisons are presented in Table 74 relating to the differences between FB, MB, and control groups in the sagittal knee angular velocity spectrum at three months post-surgery.

Table 74 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the sagittal knee angular velocity spectrum at the three months post-surgery time point during eight hours of measurement away from the laboratory during free living conditions

Three months post-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
0°/s	8.93	1.54	7.94	2.29	8.88	1.91	$p = 0.05$	3.74	-	-	-
0°/s≤ ω <25°/s	25.0	1.62	24.2	4.76	21.9	5.28	$p = 0.73$	0.31	-	-	-
25°/s≤ ω <50°/s	23.2	1.45	21.9	4.10	21.5	4.64	$p = 0.24$	1.50	-	-	-
50°/s≤ ω <75°/s	15.5	0.56	15.4	1.88	14.6	3.07	$p = 0.70$	0.36	-	-	-
75°/s≤ ω <100°/s	11.3	0.67	11.2	0.87	12.0	1.98	$p = 0.06$	3.99	-	-	-
100°/s≤ ω <200°/s	12.6	1.57	13.7	5.53	17.3	2.47	$p = 0.16$	1.97	-	-	-
200°/s≤ ω <300°/s	1.93	0.99	3.46	4.46	5.33	1.61	$p = 0.30$	1.27	-	-	-
300°/s≤ ω <400°/s	0.66	0.75	1.16	1.93	2.33	0.98	**$p < 0.05$**	4.70	0.18	0.38	1.00
400°/s≤ ω <500°/s	0.50	0.85	0.49	0.86	1.25	0.81	**$p < 0.05$**	6.63	0.49	0.34	1.00
500°/s≤ ω <600°/s	0.29	0.54	0.22	0.38	0.51	0.54	**$p < 0.05$**	3.46	1.00	0.89	1.00
600°/s≤ ω <700°/s	0.11	0.20	0.15	0.24	0.27	0.38	$p = 0.27$	1.38	-	-	-
700°/s≤ ω <800°/s	0.02	0.03	0.08	0.12	0.15	0.25	$p = 0.40$	0.95	-	-	-
800°/s≤ ω <900°/s	0.00	0.01	0.05	0.08	0.13	0.22	$p = 0.36$	1.05	-	-	-
900°/s≤ ω <1000°/s	0.00	0.00	0.03	0.04	0.09	0.17	$p = 0.30$	1.22	-	-	-

‘ω’ equates to ‘Angular velocity’; ‘SD’ to ‘Standard deviation’; ‘Sig.’ to ‘Significance of ANOVA’; ‘F’ to ‘F statistic’; ‘*’ to ‘Significant at the 0.05 level’

The greatest percentage of time spent with the knee displacing within a category of angular velocity was between 0°/s≤ω<25°/s across all groups (FB=25.0 ±1.62%; MB=24.2 ±4.76%; control=21.9 ±5.28%), similar to the findings at pre-surgery (Table 74). Comparable durations at 0°/s were observed between groups (FB=8.93 ±1.54%; MB=7.94 ±2.29%; control=8.88 ±1.91%), and consistent with the pre-surgery data, there was evidence of a considerable reduction of knee angular displacements >200°/s (FB=3.51%; MB=5.64%; control=10.1%). No significant differences were observed between groups across all incremental categories in the pairwise comparisons. Pairwise comparisons are presented in Table 75 relating to the differences between FB, MB, and control groups in the sagittal knee angular velocity spectrum at nine months post-surgery.

Table 75 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the sagittal knee angular velocity spectrum at the nine months post-surgery time point

Nine months post-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
0°/s	8.42	0.57	6.77	1.64	8.88	1.91	$p = 0.05$	3.74	-	-	-
0°/s≤ ω <25°/s	26.0	1.66	22.0	5.08	21.9	5.28	$p = 0.73$	0.31	-	-	-
25°/s≤ ω <50°/s	23.2	0.71	20.1	3.83	21.5	4.64	$p = 0.24$	1.50	-	-	-
50°/s≤ ω <75°/s	16.1	0.48	14.9	2.22	14.6	3.07	$p = 0.70$	0.36	-	-	-
75°/s≤ ω <100°/s	11.2	0.46	11.3	0.80	12.0	1.98	$p = 0.06$	3.99	-	-	-
100°/s≤ ω <200°/s	12.6	1.42	17.5	5.08	17.3	2.47	$p = 0.16$	1.97	-	-	-
200°/s≤ ω <300°/s	1.95	0.83	4.84	4.69	5.33	1.61	$p = 0.30$	1.27	-	-	-
300°/s≤ ω <400°/s	0.47	0.27	1.49	1.94	2.33	0.98	$\boldsymbol{p < 0.05}$	4.70	0.10	0.76	0.73
400°/s≤ ω <500°/s	0.11	0.07	0.57	0.86	1.25	0.81	$\boldsymbol{p < 0.05}$	6.63	0.07	0.33	1.00
500°/s≤ ω <600°/s	0.02	0.02	0.22	0.38	0.51	0.54	$\boldsymbol{p < 0.05}$	3.46	0.24	0.69	1.00
600°/s≤ ω <700°/s	0.01	0.01	0.14	0.24	0.27	0.38	$p = 0.27$	1.38	-	-	-
700°/s≤ ω <800°/s	0.01	0.01	0.07	0.12	0.15	0.25	$p = 0.40$	0.95	-	-	-
800°/s≤ ω <900°/s	0.01	0.02	0.05	0.08	0.13	0.22	$p = 0.36$	1.05	-	-	-
900°/s≤ ω <1000°/s	0.01	0.01	0.03	0.04	0.09	0.17	$p = 0.30$	1.22	-	-	-

'ω' equates to 'Angular velocity'; 'SD' to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*' to 'Significant at the 0.05 level'

At nine months post-surgery, the greatest percentage of time in the FB and MB groups was spent with the knee displacing between $0°/s \leq \omega < 25°/s$ (FB=26.0 ±1.66%; MB=22.0 ±5.08%), consistent with both the pre-surgery and three months post-surgery findings. Similar durations at 0°/s were also observed in relation to the pre-surgery and three months post-surgery findings, with the FB and MB groups spending 8.42 ±0.57% and 6.77 ±1.64%, respectively, with a constant knee angle magnitude. Further, a reduction in time spent with the knee displacing ≥200°/s was observed in line with the findings from pre-surgery and three months post-surgery. The FB and MB groups displayed angular velocities above this threshold for 2.58% and 7.41% of the eight hour measurement period, respectively. Significance was not reached between groups across all incremental categories. The combined between-group results of the sagittal knee angular velocity spectrum across FB, MB, and control groups at pre-surgery, three months post-surgery, and nine months post-surgery time points are graphically depicted in Figure 16.

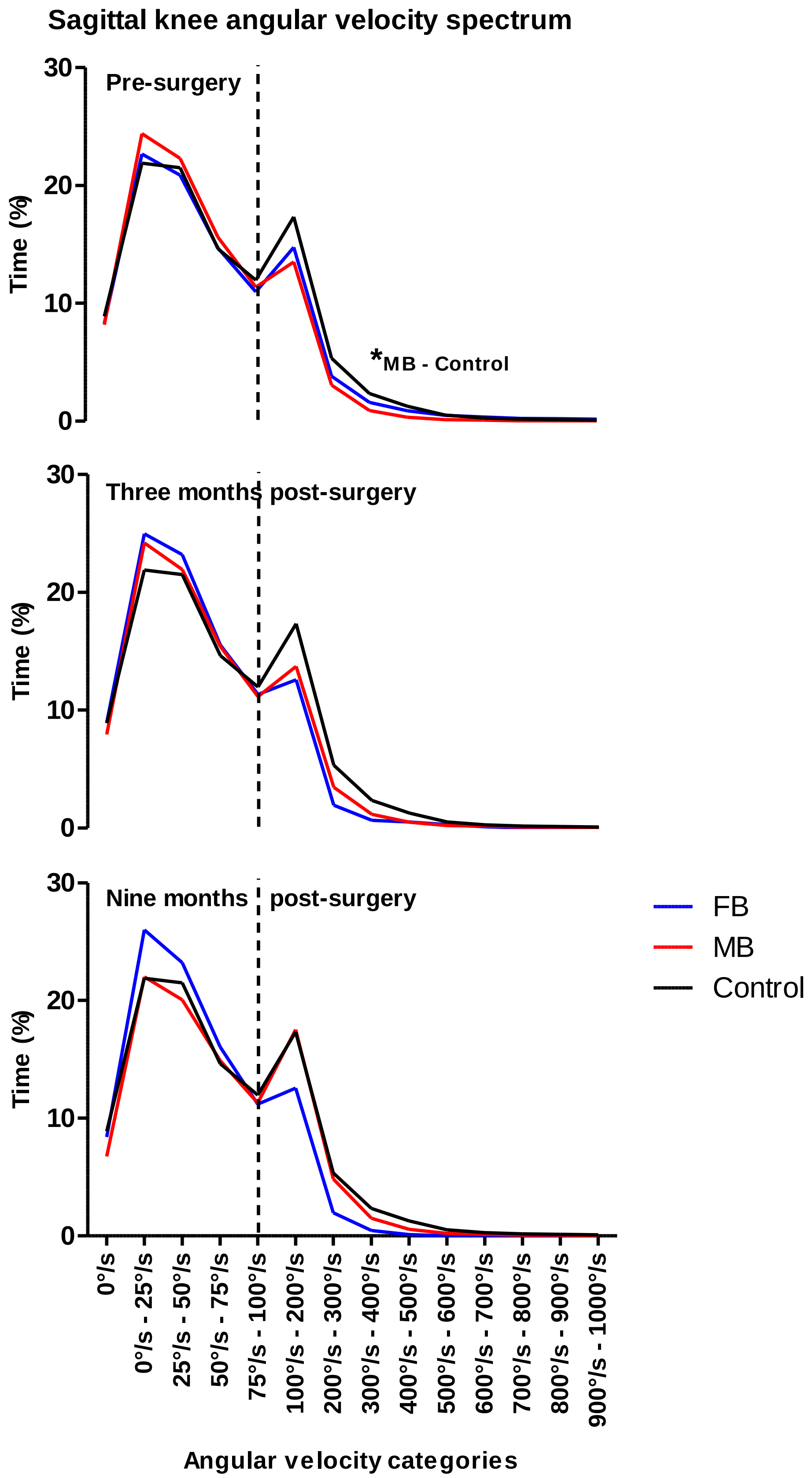

Figure 16 – Sagittal knee angular velocity spectrum of fixed bearing (FB), mobile bearing (MB), and control participants at pre-surgery, three months post-surgery, and nine months post-surgery during eight hours of ambulatory measurement between 8.00 am and 4.00 pm. Significant between group differences (p<0.05) are depicted by the asterisks (*). The vertical line (---) denotes the change in x axis

Table 76 presents differences between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, relating to the sagittal knee angular velocity spectrum.

Table 76 – Pre-surgery, three months post-surgery, and nine months post-surgery between time point differences of sagittal knee angular velocities in fixed bearing (FB) and mobile bearing (MB) participants

		Time point		Pre-3PS	3PS-9PS	Pre-9PS
		Sig.	F	*p* value	*p* value	*p* value
FB	0°/s	*p* = 0.27	1.36	-	-	-
	0°/s≤ ω <25°/s	*p* = 0.65	0.44	-	-	-
	25°/s≤ ω <50°/s	*p* = 0.56	0.60	-	-	-
	50°/s≤ ω <75°/s	*p* = 0.65	0.44	-	-	-
	75°/s≤ ω <100°/s	*p* = 0.92	0.04	-	-	-
	100°/s≤ ω <200°/s	*p* = 0.39	0.98	-	-	-
	200°/s≤ ω <300°/s	*p* = 0.73	0.31	-	-	-
	300°/s≤ ω <400°/s	*p* = 0.65	0.44	-	-	-
	400°/s≤ ω <500°/s	*p* = 0.52	0.67	-	-	-
	500°/s≤ ω <600°/s	*p* = 0.32	1.20	-	-	-
	600°/s≤ ω <700°/s	*p* = 0.16	2.12	-	-	-
	700°/s≤ ω <800°/s	*p* = 0.06	4.10	-	-	-
	800°/s≤ ω <900°/s	***p* < 0.05**	5.40	*	1.00	*
	900°/s≤ ω <1000°/s	***p* < 0.05**	6.25	*	1.00	*
MB	0°/s	*p* = 0.27	1.36	-	-	-
	0°/s≤ ω <25°/s	*p* = 0.65	0.44	-	-	-
	25°/s≤ ω <50°/s	*p* = 0.56	0.60	-	-	-
	50°/s≤ ω <75°/s	*p* = 0.65	0.44	-	-	-
	75°/s≤ ω <100°/s	*p* = 0.92	0.04	-	-	-
	100°/s≤ ω <200°/s	*p* = 0.39	0.98	-	-	-
	200°/s≤ ω <300°/s	*p* = 0.73	0.31	-	-	-
	300°/s≤ ω <400°/s	*p* = 0.65	0.44	-	-	-
	400°/s≤ ω <500°/s	*p* = 0.52	0.67	-	-	-
	500°/s≤ ω <600°/s	*p* = 0.32	1.20	-	-	-
	600°/s≤ ω <700°/s	*p* = 0.16	2.12	-	-	-
	700°/s≤ ω <800°/s	*p* = 0.06	4.10	-	-	-
	800°/s≤ ω <900°/s	***p* < 0.05**	5.40	1.00	1.00	1.00
	900°/s≤ ω <1000°/s	***p* < 0.05**	6.25	1.00	1.00	1.00

'ω' to 'Angular velocity'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'; '*' to 'Significant at the 0.05 level'; 'PS' to 'Post-surgery'

Only the FB group reached significance in the pairwise comparisons. Reductions were observed from pre-surgery to three months post-surgery in the amount of time spent with the knee displacing between 800°/s≤ω<900°/s ($F_{1.04,15.61}$ = 5.40; p<0.05), and 900°/s≤ω<1000°/s ($F_{1.02,15.36}$ = 6.25; p<0.05). Reductions were also apparent from pre-surgery to nine months post-surgery in the percentage of time between 800°/s≤ω<900°/s ($F_{1.04,15.61}$ = 5.40; p<0.05), and 900°/s≤ω<1000°/s ($F_{1.02,15.36}$ = 6.25; p<0.05).

8.3.3 Acceleration spectrum

Pairwise comparisons are presented in Table 77 relating to the differences between FB, MB, and control groups in the gross acceleration spectrum at pre-surgery.

Table 77 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the gross acceleration spectrum at the pre-surgery time point

Pre-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
$0m/s^2$	83.5	5.83	76.7	11.0	84.4	5.15	$\boldsymbol{p < 0.05}$	3.52	1.00	0.24	0.38
$0m/s^2 \leq a < 0.25m/s^2$	7.57	4.32	8.46	3.30	4.97	4.97	$\boldsymbol{p < 0.05}$	3.77	0.80	0.54	1.00
$0.25m/s^2 \leq a < 0.5m/s^2$	4.01	2.61	6.50	4.37	1.25	0.81	$\boldsymbol{p < 0.05}$	26.2	0.19	*****	0.39
$0.5m/s^2 \leq a < 0.75m/s^2$	2.57	2.69	4.02	2.82	1.16	0.80	$\boldsymbol{p < 0.05}$	9.34	0.67	0.10	0.81
$0.75m/s^2 \leq a < 1m/s^2$	1.81	2.16	2.71	1.56	1.53	0.98	$p = 0.35$	1.01	-	-	-
$1m/s^2 \leq a < 1.25m/s^2$	0.49	0.52	1.00	0.64	2.24	1.78	$\boldsymbol{p < 0.05}$	4.87	*****	0.28	1.00
$1.25m/s^2 \leq a < 1.5m/s^2$	0.12	0.06	0.28	0.22	2.81	2.90	$\boldsymbol{p < 0.05}$	10.8	*****	0.09	1.00
$1.5m/s^2 \leq a < 1.75m/s^2$	0.08	0.05	0.16	0.13	0.78	0.83	$\boldsymbol{p < 0.05}$	7.41	0.06	0.17	1.00
$1.75m/s^2 \leq a < 2m/s^2$	0.05	0.04	0.06	0.05	0.09	0.10	$p = 0.32$	1.18	-	-	-
$2m/s^2 \leq a < 2.25m/s^2$	0.03	0.02	0.04	0.04	0.08	0.11	$p = 0.13$	2.39	-	-	-
$2.25m/s^2 \leq a < 2.5m/s^2$	0.02	0.01	0.02	0.02	0.04	0.06	$p = 0.12$	2.43	-	-	-
$2.5m/s^2 \leq a < 2.75m/s^2$	0.01	0.02	0.01	0.01	0.05	0.09	$p = 0.10$	2.94	-	-	-
$2.75m/s^2 \leq a < 3m/s^2$	0.00	0.01	0.00	0.01	0.04	0.09	$p = 0.11$	2.73	-	-	-

‘a’ equates to ‘Acceleration’; ‘SD’ to ‘Standard deviation’; ‘Sig.’ to ‘Significance of ANOVA’; ‘F’ to ‘F statistic’

The greatest percentage of the eight hour measurement period across all groups was spent with the participants not eliciting an acceleration of ≥0.001664g (ActiGraph count threshold), and therefore $0 m/s^2$ (Table 77). Magnitudes of 83.5 ±5.83%, 76.7 ±11.0%, and 84.4 ±5.15% were derived for FB, MB, and control groups, respectively. Physical activity accelerations greater than the count threshold and less than $0.25 m/s^2$ accounted for 7.57 ±4.32 %, 8.46 ±3.30 %, and 4.97 ±4.97 % of the measurement period in FB, MB, and control groups, respectively. Fixed bearing and MB groups exhibited typically fewer physical activity accelerations at $\geq 1 m/s^2$ than controls (FB=0.80%; MB=1.57%; control=6.13%). The MB group (6.50 ±4.37%) displayed greater accelerations than the control group (1.25 ±0.81%) between $0.25 m/s^2 \leq a < 0.5 m/s^2$ ($F_{1.48,23.68} = 26.2$; $p<0.05$). The FB group spent a reduced amount of time between $1 m/s^2 \leq a < 1.25 m/s^2$ ($F_{2,32} = 4.87$; $p<0.05$) and $1.25 m/s^2 \leq a < 1.5 m/s^2$ ($F_{1.38,22} = 10.8$; $p<0.05$) than controls. Pairwise comparisons are presented in Table 78 relating to the differences between FB, MB, and control groups in the gross acceleration spectrum at three months post-surgery.

Table 78 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the gross acceleration spectrum at the three months post-surgery time point

Three months post-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
$0 m/s^2$	83.0	6.43	80.6	6.09	84.4	5.15	$\boldsymbol{p < 0.05}$	3.52	1.00	0.83	1.00
$0 m/s^2 \leq a < 0.25 m/s^2$	7.70	2.94	8.79	3.02	4.97	4.97	$\boldsymbol{p < 0.05}$	3.77	0.59	0.32	1.00
$0.25 m/s^2 \leq a < 0.5 m/s^2$	3.87	1.52	4.85	2.25	1.25	0.81	$\boldsymbol{p < 0.05}$	26.2	*****	*****	0.85
$0.5 m/s^2 \leq a < 0.75 m/s^2$	1.99	1.32	2.45	1.36	1.16	0.80	$\boldsymbol{p < 0.05}$	9.34	0.53	0.19	1.00
$0.75 m/s^2 \leq a < 1 m/s^2$	1.24	0.97	1.65	0.76	1.53	0.98	$p = 0.35$	1.01	-	-	-
$1 m/s^2 \leq a < 1.25 m/s^2$	0.90	1.51	1.16	0.99	2.24	1.78	$\boldsymbol{p < 0.05}$	4.87	0.33	0.70	1.00
$1.25 m/s^2 \leq a < 1.5 m/s^2$	0.88	1.94	0.25	0.19	2.81	2.90	$\boldsymbol{p < 0.05}$	10.8	0.32	0.17	1.00
$1.5 m/s^2 \leq a < 1.75 m/s^2$	0.29	0.61	0.10	0.08	0.78	0.83	$\boldsymbol{p < 0.05}$	7.41	0.47	0.25	1.00
$1.75 m/s^2 \leq a < 2 m/s^2$	0.05	0.06	0.05	0.05	0.09	0.07	$p = 0.32$	1.18	-	-	-
$2 m/s^2 \leq a < 2.25 m/s^2$	0.02	0.03	0.03	0.03	0.08	0.11	$p = 0.13$	2.39	-	-	-
$2.25 m/s^2 \leq a < 2.5 m/s^2$	0.01	0.01	0.02	0.03	0.04	0.06	$p = 0.12$	2.43	-	-	-
$2.5 m/s^2 \leq a < 2.75 m/s^2$	0.00	0.00	0.01	0.01	0.05	0.09	$p = 0.10$	2.94	-	-	-
$2.75 m/s^2 \leq a < 3 m/s^2$	0.00	0.01	0.01	0.01	0.04	0.09	$p = 0.11$	2.73	-	-	-

'a' equates to 'Acceleration'; 'SD' to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'

A similar trend was observed as that displayed at pre-surgery. All groups spent the greatest amount of time with the participants not eliciting an acceleration of ≥0.001664g (ActiGraph count threshold), and therefore $0 m/s^2$ (FB=83.0 ±6.43%; MB=80.6 ±6.09%; control=84.4 ±5.15%) (Table 78). An incremental reduction trend was evident amongst categories with few physical activity accelerations $\geq 1 m/s^2$ (FB=2.15%; MB=1.63%; control=6.13%). Both the FB ($F_{1.48,23.68} = 26.2$; $p<0.05$) and MB groups ($F_{1.48,23.68} = 26.2$; $p<0.05$) displayed reduced physical activity accelerations when compared to controls between $0.25 m/s^2 \leq a < 0.5 m/s^2$. Pairwise comparisons are presented in Table 79 relating to the differences between FB, MB, and control groups in the gross acceleration spectrum at nine months post-surgery.

Table 79 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences in the gross acceleration spectrum at the nine months post-surgery time point

Nine months post-surgery	FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
	Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p* value	*p* value	*p* value
$0 m/s^2$	79.6	8.00	80.8	8.75	84.4	5.15	$\boldsymbol{p < 0.05}$	3.52	0.65	1.00	1.00
$0 m/s^2 \leq - < 0.25 m/s^2$	8.26	3.96	8.85	3.89	4.97	4.97	$\boldsymbol{p < 0.05}$	3.77	0.50	0.42	1.00
$0.25 m/s^2 \leq - < 0.5 m/s^2$	4.35	2.13	4.87	2.60	1.25	0.81	$\boldsymbol{p < 0.05}$	26.2	*****	*****	1.00
$0.5 m/s^2 \leq - < 0.75 m/s^2$	2.53	1.43	2.19	0.97	1.16	0.80	$\boldsymbol{p < 0.05}$	9.34	0.08	0.35	1.00
$0.75 m/s^2 \leq - < 1 m/s^2$	2.59	2.12	1.43	0.37	1.53	0.98	$p = 0.35$	1.01	-	-	-
$1 m/s^2 \leq - < 1.25 m/s^2$	1.55	1.57	0.92	0.38	2.24	1.78	$\boldsymbol{p < 0.05}$	4.87	1.00	0.41	1.00
$1.25 m/s^2 \leq - < 1.5 m/s^2$	0.75	1.44	0.41	0.25	2.81	2.90	$\boldsymbol{p < 0.05}$	10.8	0.21	0.17	1.00
$1.5 m/s^2 \leq - < 1.75 m/s^2$	0.21	0.28	0.21	0.19	0.78	0.83	$\boldsymbol{p < 0.05}$	7.41	0.20	0.29	1.00
$1.75 m/s^2 \leq - < 2 m/s^2$	0.07	0.06	0.13	0.15	0.09	0.07	$p = 0.32$	1.18	-	-	-
$2 m/s^2 \leq - < 2.25 m/s^2$	0.04	0.04	0.10	0.12	0.08	0.11	$p = 0.13$	2.39	-	-	-
$2.25 m/s^2 \leq - < 2.5 m/s^2$	0.03	0.03	0.06	0.09	0.04	0.06	$p = 0.12$	2.43	-	-	-
$2.5 m/s^2 \leq - < 2.75 m/s^2$	0.01	0.02	0.03	0.05	0.05	0.09	$p = 0.10$	2.94	-	-	-
$2.75 m/s^2 \leq - < 3 m/s^2$	0.01	0.02	0.03	0.04	0.04	0.09	$p = 0.11$	2.73	-	-	-

'a' equates 'Acceleration'; 'SD' to 'Standard deviation'; 'Sig.' to 'Significance of ANOVA'; 'F' to 'F statistic'

Similar to both pre-surgery and three months post-surgery, the greatest percentage duration of the measurement period at nine months post-surgery was observed with the participants not eliciting an acceleration of ≥0.001664g (ActiGraph count threshold), and therefore $0m/s^2$ (FB=79.6 ±8.00%; MB=80.8 ±8.75%; control=84.4 ±5.15%). In a comparable observation to the MB group at pre-surgery, in addition to both the FB and MB groups at three months post-surgery, the FB ($F_{1.48,23.68} = 26.2$; $p<0.05$) and MB groups ($F_{1.48,23.68} = 26.2$; $p<0.05$) at nine months post-surgery exhibited a reduced percentage of time between $0.25m/s^2 \leq a < 0.5m/s^2$ than controls. The combined results of the gross acceleration spectrum across FB, MB, and control groups at pre-surgery, three months post-surgery, and nine months post-surgery are graphically depicted in Figure 17. No differences were found between pre-surgery, three months post-surgery, and nine months post-surgery in FB and MB groups, therefore the table was not presented.

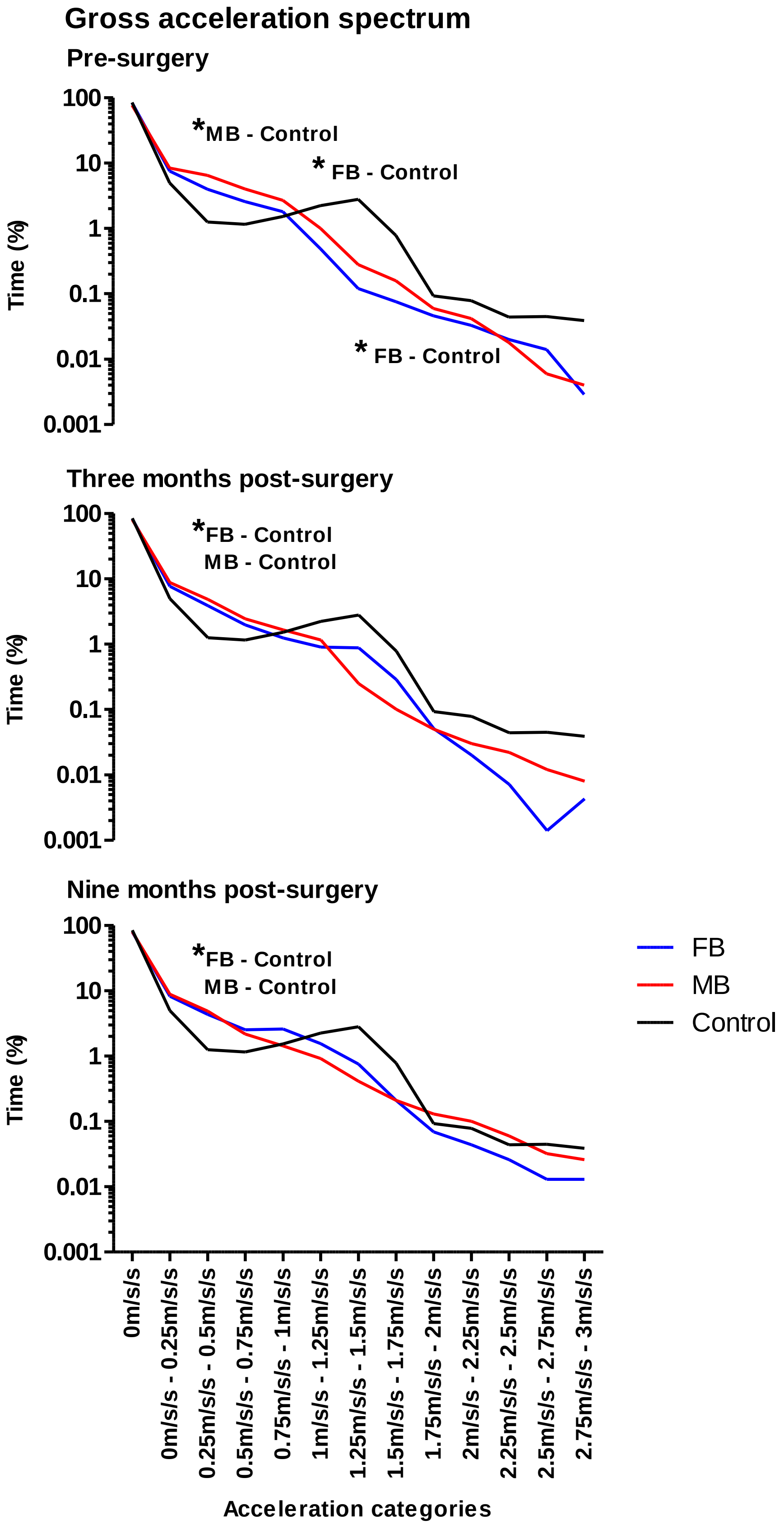

Figure 17 – Gross acceleration spectrum of fixed bearing (FB), mobile bearing (MB), and control participants at pre-surgery, three months post-surgery, and nine months post-surgery during eight hours of ambulatory measurement between 8.00 am and 4.00 pm. Significant between group differences ($p < 0.05$) are depicted by the asterisks (*)

8.3.3 Number of steps undertaken

Pairwise comparisons are presented in Table 80 relating to the differences between FB, MB, and control groups in the number of steps undertaken at pre-surgery, three months post-surgery, and nine months post-surgery.

Table 80 – Fixed bearing (FB), mobile bearing (MB), and control participant between group differences of number of steps undertaken at pre-surgery, three months post-surgery, and nine months post-surgery time points

		FB		MB		Control		Group		FB-Control	MB-Control	FB-MB
		Mean	SD	Mean	SD	Mean	SD	Sig.	F	*p*	*p*	*p*
Pre-surgery	Steps (*n*)	4073	2394	4354	1235	6472	4148	$\boldsymbol{p < 0.05}$	6.14	0.26	0.49	1.00
Three months post-surgery	Steps (*n*)	3571	2077	4767	1975	6472	4148	$\boldsymbol{p < 0.05}$	6.14	0.35	0.54	1.00
Nine months post-surgery	Steps (*n*)	4513	2602	3664	1853	6472	4148	$\boldsymbol{p < 0.05}$	6.14	1.00	0.19	0.41

‘SD’ equates to ‘Standard deviation’; ‘Sig.’ to ‘Significance of ANOVA’; ‘F’ to ‘F statistic’; ‘*’ to ‘Significant at the 0.05 level’

At all time points, no differences were found in the pairwise comparisons between groups (Table 80). No differences were found between pre-surgery, three months post-surgery, and nine months post-surgery time points in FB and MB groups, therefore the table was not presented.

8.4 Discussion

The primary aim of this chapter was to analyse whether patients implanted with MB total knee prostheses exhibited different patterns of sagittal knee kinematics and physical activity than patients implanted with FB designs during free living conditions away from the laboratory. No significant differences ($p<0.05$), or differences greater than the minimum detectable change (MDC) magnitudes calculated in Chapter 7, were observed in sagittal knee kinematics or physical activity between FB and MB groups within any of the spectral categories, supporting the findings in the gait laboratory (Chapters 5 and 6). The axial mobility of the MB prosthesis did not appear to definitively result in the MB group using their knee at greater degrees of flexion, over longer periods of time. Despite this, there was evidence of interesting trends between FB and MB groups that did not reach significance. At nine months post-surgery, the FB group exhibited a reduced mean ROM, not exceeding that of 80°. The MB group, however, exhibited a mean ROM up to 120°, similar to that of control group. This was coupled with the FB group displaying a reduced mean sagittal knee angular displacement velocity between 100°/s-200°/s at nine months post-surgery compared to the MB group. Unlike the findings of Chapters 5 and 6, these data may provide evidence of potential trends that warrant further investigation.

Although no differences between FB and MB groups were indicated, the results of this study provide an important original insight into the sagittal knee kinematic spectrum during free living conditions in TKR patients. In combined FB and MB groups, few angular displacements greater than 100° in the affected knee were observed prior to unilateral TKR surgery. A small percentage of the measurement period was observed above this threshold (FB=4.96%; MB=0.45%), with the MB group undertaking fewer ($p<0.05$) knee angular displacements than controls between 100°-110° (MB=0.45%; control=4.91%), although this difference was less than the MDC values. These results are comparable to the pre-surgery findings of Myles et al. [190], who found that patients did not exhibit knee angular displacements above 100° when the upper standard deviation (SD) limit was observed during eleven functional activities inclusive of walking, slope ascent and descent, stair negotiation, sitting into and standing out of a low and standard chair, and getting into and out of bath. The findings of the current study also support reports by van der Linden et al. [184] and Myles et al. [266] who detailed that sagittal knee excursions covering the eleven functional activities did not exceed 100° when the upper SD limit was observed. Nutton et al. [265] also found no knee angular displacements above 100° at pre-surgery in patients due to receive either a standard or a high flexion posterior stabilised TKR during a range of functional activities, apart from that of maximally flexing the knee whilst standing which is not a recognised ADL. The results of the current study provide an important validation of the previous laboratory findings of knee functional ROM in patients with late stage knee osteoarthritis (OA) prior to TKR surgery.

At the pre-surgery time point, both FB and MB groups spent the greatest percentage duration of the measurement period with the affected knee flexed between 0°-10° (FB=15.9 ±21.2%; MB=21.1 ±11.6%). When combined with the number of steps, these results support the laboratory findings of Chapter 5 in that ambulation was likely to be level walking, and not stair activity due to the large distribution of time spent with the knee displacing between 0°-10° (Figure 15). This was likely to be caused by the limiting concurrent pain and stiffness associated with late stage OA [281, 282], thus causing the patients to undertake a conscious effort to keep the knee in extension for longer periods. The results of the Oxford Knee Score (OKS) analysis in Chapter 5 (Table 36) were indicative of 'moderate to severe osteoarthritis' [225], thus supporting the assertion of a considerable symptomatic burden on these patients at pre-surgery. This prolonged extension trend has been anecdotally hypothesised amongst orthopaedic surgeons, but has not been previously confirmed using electrogoniometry. Laboratory based studies have found that the range of 0°-10° is inclusive of the minimum angle required for the performance of the eleven functional activities studied in patients with late stage OA [190], but no previous research has quantified the spectrum of sagittal knee kinematics during free living conditions.

The pre-surgery sagittal knee angular displacement spectrum was also indicative of a pronounced, but less substantial peak between 40°-50°. As found in Chapters 5 and 6 during walking and stair negotiation activities, the range of 40°-50° was inclusive of the swing phase of walking, the stance phase of stair ascent, and proportions of both stance and swing during stair descent in these patients. This peak was likely to be a product of ambulatory activity, with over 4000 steps being undertaken in FB and MB patients (FB=4073 ±2394; MB=4354 ±1235). Previous authors using electrogoniometry have also observed that this range was inclusive of a number of ADLs in patients with late stage OA [184, 190, 265, 266].

The collated spectrums of knee angular velocity and gross acceleration provide information about the physical activity patterns undertaken, and were suggestive of little physical activity in both the FB and MB groups at pre-surgery. The greatest percentage duration of angular velocity across the TKR groups was spent with the knee displacing between 0°/s-25°/s, with almost 25%, or 2 hours of the measurement period, observed within this range (FB=22.7 ±2.93%; MB=24.4 ±2.21%). Angular displacements at the knee of 0°/s, indicative of a fixed joint position, were found to constitute a magnitude of 8.32 ±0.50% and 8.18 ±1.61% in FB and MB groups, respectively. When combining both incremental categories, approximately 30% of the measurement period was inclusive of angular displacements between 0°/s-25°/s. Smith et al. [283] reported pre-surgery knee angular velocities during different phases of the gait cycle and found the maximum knee angular velocity to be during the knee flexion displacement to maximum knee flexion in swing, deriving a magnitude of 57°/s (LCI=37°/s; UCI=76°/s). The period to maximum mid stance flexion was indicative of the lowest angular velocity (32°/s; LCI=11°/s; UCI=53°/s), however, this magnitude was still greater than the category encompassing the largest percentage of angular displacements in the current investigation (0°/s-25°/s). The lower angular velocities observed in the current investigation were therefore likely to be more indicative of small movements of the knee whilst sitting, or an equivalent activity where the patient is largely immobile, rather than ambulatory activities that have been shown to exhibit greater magnitudes of angular velocity at the knee [283].

The postulation of a largely sedentary behaviour pattern at the pre-surgery time point was supported by the findings from the physical activity accelerations. The FB and MB groups exhibited percentage durations of 83.5% ±5.83% and 76.7% ±11.03% at a magnitude of $0 m/s^2$, respectively, although the TKR groups did not differ from the controls (84.4% ±5.15%). These results indicate prolonged periods of inactivity over the eight hour measurement period. In the only other study combining electrogoniometry and accelerometry for the measurement of an orthopaedic population during free living conditions, Morlock et al. [268] derived comparable results over approximately nine hours of monitoring with 71.1% of the measurement period spent with the patients in static positions following total hip replacement surgery. The combined kinematic and physical activity results of the current study suggest that the initiation of motion from resting might be important for more realistic testing conditions for future laboratory studies analysing TKR populations.

At three months post-surgery a similar 'double peak' trace was apparent in the knee angular displacement spectrum, although less pronounced, but also with the initial peak skewed towards a more flexed position (20°-40°) than pre-surgery (0°-10°). This finding corresponds to the increased flexion trend in Chapter 5 during the stance phase of walking in both FB and MB groups (Figure 13), a finding attributed to increased quadriceps activation in the absence of optimised anterior stability due to the excision of the ACL. Despite this, within FB and MB group differences from pre-surgery to three months post-surgery in these categories did not reach significance ($p>0.05$) and were also less than the MDC values. No previous studies have assessed TKR patients as little as three months post-surgery using electrogoniometry, although Myles et al. [190] and Myles et al. [266] reported findings at four months post-surgery. Myles et al. [190] found reductions ($p<0.008$) in knee flexion from pre-surgery to four months post-surgery during the performance of sitting into and standing out of a low chair, into and out of a standard chair, and getting into and out of a bath. No differences were observed in walking, slope ascent and descent, and stair ascent and descent, activities that required lower magnitudes of knee flexion excursion.

After a further six months of rehabilitation, a similar percentage duration was evident in FB and MB groups between 0°-10° as that at three months post-surgery, and was subsequently found to be not significant (p>0.05; <MDC) within groups. The FB group ambulated with a greater (p<0.05; >MDC) percentage duration between 30°-40° at nine months post-surgery (22.7 ±15.5%) than three months post-surgery (7.32 ±4.95%), suggesting an increased flexion trend over the measurement period. When the results at nine months post-surgery were compared to those at pre-surgery, an unexpected reduction (p<0.05) was observed between 110°-120° in the FB group. Significance was likely reached in this incidence, however, due to the small magnitudes of percentages involved. This difference was also less than the MDC values.

A number of authors have assessed patients during functional activity at a period following adequate rehabilitation [184, 190, 265, 266]. At one year post-surgery, Nutton et al. [265] only reported maximal knee flexion whilst standing to exceed 100° of flexion. Unfortunately, statistical analyses were not undertaken between pre-surgery and one year post-surgery time points as their objective was to compare standard and high flexion TKR prostheses. Myles et al. [190] reported maximum knee flexion angles of 81.3° at 18 to 24 months post-surgery during the eleven functional activities previously described. Van der Linden et al. [184], Myles et al. [266], and Myles et al. [190] all reported knee excursions at 18 to 24 months post-surgery that did not exceed 77.1°. These findings support the angular displacement observations of the current investigation at nine months post-surgery, with few observations of displacements greater than 100° (FB=0%; MB=1.97%). Rowe et al. [153] suggested that 110° would be a suitable target for the rehabilitation of knee joint function following nonspecific knee injury or surgery. The results from the current study appear to support these recommendations in patients following TKR surgery.

No significant differences, or differences greater than the MDC values, were also observed between FB and MB prostheses at nine months post-surgery in the angular velocity spectrum. A similar trend was apparent when compared to both pre-surgery and three months post-surgery, with the largest percentage duration between 0°/s-25°/s (FB=26.0 ±1.66%; MB=22.0 ±5.08%). This suggestion was compounded with the finding of no significant differences within the FB group between nine months post-surgery and either pre-surgery or three months post-surgery from 0°/s-800°/s, with no differences in the MB group. In a study of unicompartmental and posterior cruciate ligament (PCL) retained TKR patients, Jevsevar et al. [284] reported knee angular velocities during a range of functional activities between 12 to 19 months post-surgery. Unfortunately, the authors only reported maximum angular velocities, rather than means across the displacement cycles. The lowest maximum knee angular velocity reported by Jevsevar et al. [284] was 40.9 ±11.6 °/s during the stance phase of stair descent, a magnitude greater than the category encompassing the largest percentage of angular displacements in the current investigation ($0°/s \leq \omega < 25°/s$). The physical activity acceleration spectrum in the current investigation was also similar to the assessments at pre-surgery and three months post-surgery. Significance was not reached between FB and MB groups, with no significant differences also found in the within group between time point analysis, in addition to no differences greater than the MDC values.

8.4.1 Limitations

The main limitation of this study is that due to the moderate errors identified in Chapter 7 with regards to between-session physical activity patterns, the testing session undertaken may not have been entirely representative of a normal period of physical activity. Good validity and between-session reliability of the electrogoniometry system over specific ADLs in the laboratory was also found in Chapter 7. Calculation of the MDC magnitudes in Chapter 7 enabled valid continuation of testing using the system for comparison of groups and also aids the contextual interpretation of the statistical analyses.

Due to logistical reasons discussed in Chapter 7, in addition to the limited battery life of the system which has been experienced by previous authors [82, 146, 268], testing over longer and multiple periods was not possible in this instance. It was decided against normalising to a longer measurement period, such as 12 hours. Doing so could have potentially overestimated real physical activity levels, since the measurements covered the most active time periods of the day [268]. A further limitation is that since the patients were informed regarding the purpose of the study, some patients may have tried to be as active as possible during the measurement period.

Across all experimental groups and time points, there was a mean range of 6.77%-8.93% of the measurement period spent with the knee displacing at 0°/s in the angular velocity spectrum. In reality, this is unlikely to be the case due to the inherent noise within the signal of the electrogoniometer, and is therefore more likely to be a product of the rounding procedure used during analysis. Despite this, 0°/s in this instance still provides a good representation of no gross knee movement, as any residual movement would likely result in values greater than the 3 decimal digits of precision that was used, i.e. >0.0005.

8.5 Conclusions

- No differences were found between FB and MB groups in the inferential statistical analyses. There were also no differences greater than the MDC magnitudes determined in Chapter 7.
- Both FB and MB groups spent the greatest duration of the measurement period at pre-surgery with the knee flexed between 0°-10°. Following an adequate period of rehabilitation at 9 months post-surgery, more time was spent with the knee displacing at greater degrees of flexion.
- These results validate the previous laboratory findings that suggest 110° of flexion would be a suitable target for rehabilitation following TKR surgery.
- Both patient groups undertook little physical activity during the measurement period, with approximately 80% of the measurement period spent with the patients being inactive across all time points.

9.0 General discussion

9.1 Key findings from this thesis

- There appeared to be no biomechanical advantage of mobile bearing (MB) implantation during walking over fixed bearing (FB) designs.

- There appeared to be no biomechanical advantage of MB implantation during stair negotiation, sit to stand, and stand to sit activities over FB designs.

- There appeared to be no biomechanical advantage of MB implantation during free living conditions away from the laboratory over FB designs.

9.2 Discussion of key findings

The primary aim of this thesis was to determine whether MB total knee prostheses offered biomechanical advantages over FB designs during activities of daily living (ADLs). In order to provide a more objective measure, this thesis employed three dimensional motion analysis as a primary measurement tool which can quantify kinematics and kinetics about the knee to a high degree of accuracy [73]. The results of the systematic review and meta-analysis in Chapter 2 suggested that few data pertain to the functional comparison of FB and MBs designs using gait analysis during ADLs [10, 29, 77-80]. Discrepancies in methodological design, methodological reporting, and gait variables between the studies were also prevalent, limiting the collated findings and providing support for further research. Electrogoniometry and accelerometry were also applied in the measurement of sagittal knee kinematics and physical activity during free living conditions away from the laboratory. The integration of systems that enable measurement away from the laboratory with traditional laboratory based three dimensional motion analysis systems has been determined to enhance the clinical relevance of findings [285]. Few data are available in this pioneering area [82, 146, 268], with no studies comparing FB and MB designs.

Catani et al. [29] and Fantozzi et al. [79] detailed gait patterns that were conducive of instability during stair negotiation in MB implanted knees, suggesting functional disadvantages of the MB paradigm. As a secondary aim to this thesis, these previous limited findings of disadvantageous compensatory mechanisms in MBs were assessed. In addition to being of direct relevance to patient functional outcome following surgery [74-76] and influencing implant longevity [8], the questions considered by this thesis will have also been of interest to hospital commissioners, with the published cost of MBs 35% more than FBs [286]. This poses the question as to whether MBs are worth the additional expense from a functional perspective.

Prior to comparing the resultant lower limb biomechanics of FB and MB implanted patients, Chapter 4 determined both the within-session and between-session reliability of gait analysis data collected within the laboratory. It was important to quantify the within-session variation from trial to trial in FB, MB, and age and gender matched control participants in order to aid the interpretation of the inferential statistical analyses between groups in Chapters 5 and 6, with knowledge of this important in determining the level of detectable change [151]. The incorporated between-session reliability analysis of kinematic data was of equal importance in order to determine the effect of marker placement discrepancies between-sessions, the primary cause of extrinsic variation in gait analyses [176]. The within-session analysis demonstrated good overall reliability, with some findings of moderate reliability in spatiotemporal variables during stair negotiation which were likely due to the greater biomechanical demands [181, 183-187], analysis of the first step [188], and the inclusion of fewer patients and trials due to the cohort's relative difficulty in adequately performing stair negotiation.

The between-session analysis was also indicative of good reliability in sagittal knee kinematics, deriving minimum detectable change (MDC) magnitudes <5°, a previously defined limit for sagittal knee kinematics [170, 173, 174]. Both within-session and between-session studies derived greater errors in frontal and axial planes which is potentially caused by the smaller range of movement (ROM) at the knee in these planes compared to the noise of the data [194]. The results of Chapter 4 provided validation for the use of three dimensional motion analysis in the comparison of groups, although lower reliability was evident in the frontal and axial planes.

Chapter 5 compared FB and MB patient groups during walking at pre-surgery, three months post-surgery, and nine months post-surgery. No significant differences (p<0.05) in the pairwise comparisons or differences greater than the MDC magnitudes calculated in Chapter 4 were evident between FB and MB groups following TKR surgery. These results suggested that no biomechanical advantage was gained with MB implantation during walking, refuting the only other full text article published in English which statistically compared FB and MB groups during walking, with Kramer's de-Quervain et al. [80] detailing an increase in the maximum knee flexion of MB prostheses when compared to FBs. Mockel et al. [78] also found greater mean stance phase knee flexion in MB prostheses when compared to FBs, although only a translated abstract from a full text article published in German was available.

Chapter 5 holds a number of methodological advantages over Kramer's de-Quervain et al. [80], thus providing an important original contribution to knowledge with regards to walking between FB and MB groups. The testing of patients at pre-surgery was integral in determining whether differences were apparent prior to surgery. The post-surgery differences identified in Kramer's de-Quervain et al. [80] could potentially be due to differences at pre-surgery, although this was not assessed. This is a likely possibility as pre-surgery gait patterns can be retained up to 18 months post-surgery [117], further supporting the use of a pre-surgery time point to validate post-surgery findings. In addition, only five patients were assessed by Kramers de-Quervain et al. [80] , with no power analysis reported.

Despite the mechanical differences between FB and MB designs, one potential reason why MBs did not provide biomechanical advantages over FB designs during walking is that the sagittal knee flexion excursion did not elicit a sufficient magnitude of ROM in which the knee would require greater axial rotation. At nine months post-surgery, the sagittal ROM was under 50° in both FB (49.5 ±6.62°) and MB groups (46.8 ±9.41°). From the findings of Asano et al. [15], 50° of flexion would require 12.5° of axial rotation in the normal knee. The findings of Chapter 5, therefore, indicated that the FB design elicited enough residual axial rotation between the femoral component and the fixed tibial tray to perform adequately during walking, although it is these constrained residual rotation moments that can cause polyethylene wear and potentially lead to component loosening [20]. Another reason is that as only eight patients were recruited to each group, the post-hoc power analysis determined a 'moderate' effect between groups [113]. This suggested that when coupled with the relative biomechanical ease of walking, 'small' effects may not have been discernible from the data.

Chapter 6 was undertaken as a progression from Chapter 5 to investigate whether the greater ROM required during more biomechanically demanding ADLs would elicit advantages of the MB design. The findings of Chapter 6 indicated that the additional biomechanical difficulty of stair negotiation was unable to identify any differences following TKR surgery between FB and MB groups. No indication of instability was also identified during stair negotiation and sit to stand and stand to sit activities, refuting the preliminary findings of Catani et al. [29] and Fantozzi et al. [79].

Regardless of the additional 15°-20° of maximum knee flexion required during stair negotiation compared to walking [183, 187, 190], the results of Chapter 6 suggested that MBs do not provide biomechanical advantages over FB designs with regards to optimising knee function during stair negotiation. Previous findings of instability in MB knees were also not observed in the current cohort [29], with this potentially being due to differences in the type of MB prosthesis used. The Sigma Rotating Platform Knee System (De Puy International, Leeds, UK) utilised in the current study does not permit antero-posterior translation, although moment driven residual displacement is possible between the femoral component and polyethylene insert in the same way that a FB design allows residual axial rotation. Both MBs prostheses utilised in Catani et al. [29] and Fantozzi et al. [79] allowed antero-posterior displacement, with the findings of Chapter 6 suggesting that non-displacing antero-posterior MB designs appear preferable in stabilising the knee compared to antero-posterior displacing designs during biomechanically demanding ADLs.

Following extensive laboratory assessment in Chapters 5 and 6, Chapter 7 was undertaken to validate an electrogoniometry system against three dimensional motion analysis, in addition to determining the between-session reliability of sagittal knee kinematics and physical activity during free living conditions away from the laboratory, measured using electrogoniometry and accelerometry. The between-session reliability of the electrogoniometry system was also assessed in the laboratory over walking, stair negotiation, sit to stand, and stand to sit activities. The purpose of this work was to provide a supplementary approach to traditional laboratory testing with a view to optimising the clinical validity of the results, as laboratory assessments used as standalone methods do not always reproduce conditions that are representative of everyday living [82].

The electrogoniometry system was found to be valid when compared to three dimensional motion analysis in the first sub-study. In the second sub-study, moderate between-session error was derived in sagittal knee kinematics and physical activity between the two periods of free living away from the laboratory. The third sub-study confirmed small between-session errors in the electrogoniometry system during ADLs in the laboratory, suggesting the differences between-sessions in sagittal knee kinematics during the two periods of free living conditions were largely due to differences in physical activity patterns. Of the previous authors undertaking similar monitoring using electrogoniometry during free living conditions, none have presented reliability data [82, 146, 268], thus compromising the validity of their findings. The findings of Chapter 7, therefore, constitute an important original contribution to knowledge in this developing field. The MDC was calculated in Chapter 7 in order to allow valid use of the systems within the calculated error in Chapter 8.

Chapter 8 derived no differences between FB and MB groups in the pairwise comparisons, or differences greater than the MDC magnitudes determined in Chapter 7 when assessing sagittal knee kinematics and physical activity over an extended period during free living conditions away from the laboratory. These results suggested no conclusive differences in sagittal knee kinematic patterns or the amount of physical activity undertaken by FB and MB groups. Despite this, there was a trend suggesting that the MB patients reached a greater ROM than the FB group. The FB group at nine months post-surgery did not exceed 80° of flexion, while the MB achieved up to 120°. These data warrant further investigation with the on-going development of the system over more trials and a longer measurement period.

Despite finding no differences between FB and MB groups outside of the measurement error, Chapter 8 derived other important findings. The data suggested that 110° of flexion seems to be an appropriate target for rehabilitation following TKR surgery. This has been suggested from previous experimentation [184, 190, 265, 266], however, the findings from Chapter 8 support these laboratory based recommendations with data obtained outside of the laboratory environment. Another important finding was the observation of large periods of inactivity in the TKR cohort. This has potentially important implications for the future testing of TKR patients in the laboratory environment. During gait analyses in situations that allow, the current accepted practice is to instruct participants to undertake a number of initial gait cycles before capturing a specific gait cycle or series of cycles. The findings of Chapter 8 suggest that the initial cycles from a stationary position, either from sitting or standing, may be more representative of everyday activity in the TKR population, and thus provide a more valid assessment.

9.3 Original contributions to knowledge

- MB designs may not provide biomechanical advantages during walking over FBs using the same implant range, posterior cruciate ligament (PCL) scenario, posterior stabilising strategy, and patella strategy. The methodological strengths of this thesis compared to previous work suggest an important original contribution to current knowledge.

- MB designs may not provide biomechanical advantages or disadvantages during demanding ADLs over FBs. The decision to implant FB or MB prostheses, therefore, should be made with regards to other more pertinent considerations such as polyethylene wear rates or operator experience.

- Electrogoniometry appeared to be a valid measure of sagittal knee kinematics during ADLs, suggesting the instrumentation is suitable for use in the clinical environment.

- Between-session differences in sagittal knee kinematics and physical activity measured using electrogoniometry and accelerometry can be moderate. It is important, therefore, to determine the specific magnitude of error for valid interpretations.

- 110° of flexion at the knee appears to be an appropriate target for rehabilitation following TKR surgery. These findings validate, for the first time, previous laboratory based recommendations using data collected outside of the laboratory environment.

9.4 Limitations

A limitation of this body of work is the relatively small sample size. An a priori power calculation was undertaken at the outset of the randomised study that suggested a total sample size of 21 based on an effect size (Cohen's *f*) of 0.35 (($\geq$0.25 - <0.4 = medium [113]), an α error probability of 0.05, and a power (1-β error probability) of 0.8, in addition to three groups with three measurement periods in a within-between interaction. Twenty-four participants were recruited in total, although the sample size still did not have adequate power to detect 'small' [113] differences between groups. Despite this, the sample size was similar to previous work using gait analysis in the testing of FB and MB groups [29, 77, 79, 80], with no previous study providing evidence of an a priori power analysis [10, 29, 77, 79, 80]. Additional patients under the care of another surgeon could have been recruited, however, this was not undertaken as potential between-surgeon variability would have confounded the comparative analysis [287]. Despite the limited sample size, there appeared to be no indication of differences that may have became significant with the testing of more patients over more trials in Chapters 5 and 6.

As discussed in Chapter 6, a limitation is that due to the symptomatic burden experienced by the patients, there was a reduced number able to adequately perform the stair negotiation activities at pre-surgery and three months post-surgery, in addition to sit to stand at three months post-surgery. For the future use of biomechanically demanding activities in the testing of patients prior to, and at early time points following TKR surgery, it may be necessary to utilise instrumented handrails in order to maximise the inclusion of data in the analysis. This would be problematic, however, as standardisation would prove difficult due to the use of different techniques and magnitudes and direction of subsequent force application.

A further limitation was the determination of moderate errors in Chapter 7 relating to differences between-sessions in sagittal knee kinematics and physical activity, suggesting a ‘normal’ period of physical activity may be difficult to capture with the use of one trial. As discussed in Chapter 7, logistical factors prevented the capture of more patient trials in Chapter 8. Importantly, the MDC was calculated allowing the valid use of the systems within the pre-defined error limits. This has not been undertaken in previous research [82, 146, 268].

9.5 Future directions

Chapter 6 of this thesis has highlighted the benefit of including more biomechanically demanding ADLs in the comparison of FB and MB groups, and future studies should utilise these in the comparative analysis of orthopaedic implants in order to accentuate potential differences. In addition, gait laboratory testing capturing initial ambulation from a resting position may be more representative of free living conditions away from the laboratory due to the relative inactivity of the patients identified across all time points.

Chapter 8 demonstrated the potential for long term knee kinematic and physical activity measurements in providing objective insight into the rehabilitation status of TKR patients. The next step in this research is to undertake longer term monitoring, and develop machine learning algorithms through extensive validation and capture of routine data in the laboratory. From this, activity classification could be undertaken from kinematic and acceleration data, providing information on the activities undertaken, in addition to detailed kinematic information within specific activities. The longer term goal is to enable synchronization with medical record systems in the hospital, with automated report generation providing summaries of kinematics, activities, and physical activity over the measurement period. Such monitoring capabilities could negate the requirement for some outpatient clinical assessments following TKR if suitable progress is verified.

The findings of this thesis suggest no biomechanical advantage of MB total knee prostheses over FB designs during ADLs. There appears to be no evidenced based rationale for the widespread use of MB total knee prostheses over FB designs with regards to improved knee function. What remains unknown is the longer term function of FB and MB total knee prostheses. Multi-centre collaborations with the resources to examine patients at longer term follow-up periods are required to compare the biomechanics of FB and MB total knee prostheses throughout their life span before definitive recommendations can be produced.

10.0 Appendices

Appendix A

Published abstract

Title: Three dimensional gait analysis of fixed bearing and mobile bearing total knee prostheses during walking
Authors: Urwin SG, Kader DF, St Clair Gibson A, Caplan N, Stewart S
Conference: British Association for Surgery of the Knee (BASK), Leeds, UK, 2013

Debate is on-going regarding the hypothetical functional advantages of mobile bearing (MB) total knee prostheses, with few studies comparing fixed bearing (FB) and MB groups using three dimensional motion analysis. The aim of this study was to compare three dimensional spatiotemporal, knee kinematic, and knee kinetic parameters at pre-surgery, three months post-surgery, and nine months post-surgery during walking. Sixteen patients undergoing primary unilateral total knee replacement (TKR) surgery were randomised to receive either a FB (n = 8) or MB (n = 7) total knee prosthesis. Eight age and gender matched controls underwent the same protocol on one occasion. A 12 camera Vicon system integrated with four force plates was used. No significant differences between FB and MB groups were found at any time point in the spatiotemporal parameters. The MB group was found to have a significantly reduced frontal knee ROM at pre-surgery than the FB group (FB = 14.92 ± 4.02°; MB = 8.87 ± 4.82°), with the difference not observed at 3 or 9 months post-surgery. No further significant kinematic or kinetic differences were observed between FB and MB groups. FB and MB groups differed from controls in 3 and 7 parameters at pre-surgery, 8 and 8 parameters at 3 months post-surgery, and 6 and 5 parameters at 9 months post-surgery, respectively. No functional advantages were offered in knees implanted with MB prostheses during walking, with both groups indicative of similar differences when compared to normal knee biomechanics at 3 and 9 months following prosthesis implantation.

Appendix B

Published abstract

Title: Do mobile bearing total knee prostheses produce instability during stair ascent? A prospective randomised comparative study
Authors: Urwin SG, Kader DF, St Clair Gibson A, Caplan N, Stewart S
Conference: British Association for Surgery of the Knee (BASK), Leeds, UK, 2013

Previous authors have found that patients implanted with mobile bearing (MB) total knee prostheses display reduced maximum knee extension and adduction moments during stair ascent. These results are indicative of compensatory mechanisms that suggest instability in the MB knee. Sixteen patients undergoing primary unilateral total knee replacement (TKR) surgery were randomised to receive either a fixed bearing (FB) (n = 8) or MB (n = 8) total knee prosthesis. Eight age and gender matched controls underwent the same protocol on one occasion. A 12 camera Vicon system integrated with a force plate on the first step of a stair rig was used. Participants were tested at nine months post-surgery. No significant differences ($p <$ 0.05) were found between FB and MB groups in spatiotemporal, knee kinematic, or knee kinetic parameters. FB and MB patients ascended with significantly reduced gait velocity than controls (FB = 0.44 ±0.068m/s; MB = 0.42 ±0.05m/s; control = 0.61 ±0.12m/s), with the FB group deriving reduced stride length than controls (FB = 0.67 ±0.016m; controls = 0.76 ±0.05m). FB and MB groups ascended with reduced sagittal knee range of movement (ROM) than controls (FB = 76.08 ±9.95°; MB = 72.70 ±5.31°; control = 94.03 ± 7.59°), with the MB group observing greater minimum knee flexion than controls (MB = 20.30 ±2.87°; control = 11.55 ± 2.60°). No knee kinetic differences were found between all groups. These findings suggest that the MB implanted knee does not evoke significant instability when compared to FB designs and asymptomatic joints.

Appendix C

Published paper

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Gait analysis of fixed bearing and mobile bearing total knee prostheses during walking: Do mobile bearings offer functional advantages?

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ABSTRACT

Background: Limited previous findings have detailed biomechanical advantages following implantation with mobile bearing (MB) prostheses after total knee replacement (TKR) surgery during walking. The aim of this study was to compare three dimensional spatiotemporal, kinematic, and kinetic parameters during walking to examine whether MBs offer functional advantages over fixed bearing (FB) designs.

Methods: Sixteen patients undergoing primary unilateral TKR surgery were randomised to receive either a FB ($n = 8$) or MB ($n = 8$) total knee prosthesis. Eight age and gender matched controls underwent the same protocol on one occasion. A 12 camera Vicon system integrated with four force plates was used. Patients were tested pre-surgery and nine months post-surgery.

Results: No significant differences between FB and MB groups were found at any time point in the spatiotemporal parameters. The MB group was found to have a significantly reduced frontal plane knee range of motion (ROM) at pre-surgery than the FB group (FB = 14.92 ± 4.02°; MB = 8.87 ± 4.82°), with the difference not observed post-surgery. No further significant kinematic or kinetic differences were observed between FB and MB groups. Fixed bearing and MB groups both displayed spatiotemporal, kinematic, and kinetic differences when compared to controls. Fixed bearing and MB groups differed from controls in six and five parameters at nine months post-surgery, respectively.

Conclusions: No functional advantages were found in knees implanted with MB prostheses during walking, with both groups indicative of similar differences when compared to normal knee biomechanics following prosthesis implantation.

Level of evidence: Level II.

1. Introduction

In total knee replacement (TKR) surgery, mobile bearing (MB) prostheses facilitate planar rotation about the vertical axis of the tibia [1,2], with a view to reducing sub-surface stress through dual surface articulation at both the superior and inferior surfaces of a polyethylene insert [3,4]. Dual surface articulation promotes load sharing between the relative displacements of the tibial and femoral components, dissipating knee moments and shear forces to the surrounding soft tissues in a similar manner to the normal knee [5].

Many theoretical benefits of the MB design, including the improvement in kinematics [5], have yet to be substantiated, with numerous authors documenting no improvements in outcomes when compared to fixed bearing (FB) designs [6–10]. The majority of studies comparing FB and MB prostheses have used questionnaire based outcome measures that have been shown to be less sensitive than gait analyses when detecting changes in gait [11]. Gait analysis has been previously used to measure functional outcome following TKR surgery [12], with current systems able to calculate the biomechanics about the knee to a high degree of accuracy, establishing gait analysis as an important tool in the clinical management of knee problems [13].

Previous findings have been inconclusive in the comparison of FB and MB prostheses by means of gait analysis, with four previous authors assessing walking [14–17]. The differences in study design, instrumentation, and methods between the studies make it difficult to extract meaningful conclusions. Mockel et al. [16] and Kramers-de Quervain et al. [17] presented results in favour of MB prostheses [5] that warrant further investigation. Mockel et al. [16] found increased stance phase knee flexion in MB knees (14.1°) when compared to FB knees (10.8°), an indication of a more effective shock-absorbing mechanism during loading response [22].

Kramers-de Quervain et al. [17] detailed greater maximum knee flexion during the swing phase of gait in MB knees (52.4 ± 7.56°) when compared to FB knees (47.1 ± 4.74°) in bilaterally implanted TKR patients. A greater maximum knee flexion during swing

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demonstrates an improved ability for limb advancement and foot-clearance [18], in addition to increasing overall range of motion (ROM) which is an important determinant of functional activity following TKR surgery [19]. The aim of this study was to substantiate these previous limited findings of functional improvement in knees implanted with MB total knee prostheses during walking by means of three dimensional gait analysis.

2. Patients

Ethical approval was granted by an NHS Regional Ethics Committee. Nineteen patients with late stage primary knee osteoarthritis (OA) were recruited after giving written informed consent for participation. Patients were randomised to receive a FB (Sigma® Fixed Bearing Knee System, DePuy International, Leeds, UK) or MB (Sigma® Rotating Platform Knee System, DePuy International, Leeds, UK) total knee prosthesis. In contrast to a rotating platform where the femoral–tibial bearing surfaces are in substantial conformity from 0 to 60° of flexion, the MB knees in this study use the same multiradius femoral component and hence the femoral–tibial bearing is not in conformity.

Eight patients, five males and three females, received a FB prosthesis and had a mean age of 59.3 ± 8.8 years, height of 1.66 ± 0.09 m, mass of 87.85 ± 16.06 kg, body mass index (BMI) of 31.93 ± 4.86 kg/m^2, and pre-surgery Oxford Knee Score (OKS) of 39 ± 7.64. Eight patients, five males and three females, received a MB prosthesis and had a mean age of 59.6 ± 7.7 years, height of 1.7 ± 0.09 m, mass of 91.21 ± 12.43 kg, BMI of 31.92 ± 6.8 kg/m^2, and pre-surgery OKS of 37.42 ± 5.32. Inclusion criteria were patients between 45 and 80 years of age. Patients were excluded if they had previous hip or knee replacement surgery, gross ligament instability, valgus/varus displacement of ≥20°, significant infection of the knee joint post-surgery, or any other significant unrelated lower limb injury or chronic condition that was deemed to have the potential to affect ambulation. Both FB and MB prostheses were posterior cruciate ligament sacrificing, posterior stabilised, and had the patella resurfaced in all cases. One senior orthopaedic surgeon (DK) performed all of the procedures.

Eight age and gender matched asymptomatic participants, five males and three females, who had a mean age of 60.5 ± 7 years, height of 1.67 ± 0.12 m, mass of 72.58 ± 9.43 kg, and BMI of 26.06 ± 1.21 kg/m^2 were recruited as a control group. Table 1 details the demographic and anthropometric parameters of the FB, MB and control groups.

3. Method

3.1. Gait analysis

A 12 camera (T20, Vicon, Oxford, UK) three dimensional motion analysis system (Vicon MX, Oxford, UK) was calibrated through a standard dynamic protocol, exhibiting an image error of <0.2 mm. Participants had their height and mass taken, along with bilateral leg length, and knee and ankle widths in order to fit the participant's specific dimensions to the lower body 'Plug in Gait' model (Vicon, Oxford, UK). Fourteen retroreflective markers (Ø = 14 mm) were placed bilaterally over the anterior superior iliac spine, posterior superior iliac spine, lateral distal third of the thigh, lateral distal third of the shank, lateral malleolus, heel on the calcaneus, and the head of the second metatarsal. Kinematic data were subsequently captured at 200 Hz into Vicon Nexus (1.7.1, Vicon, Oxford, UK).

Four force plates (OR6-7, AMTI, Watertown MA, USA) were embedded within a 7 m walkway and amplified into Nexus at a gain of 1000 (MiniAmp MSA-6, AMTI, Watertown MA, USA), with kinetic data captured at 1000 Hz. Two knee alignment devices ((KADs) Vicon, Oxford, UK) were then placed bilaterally over the medial and lateral epicondyles to independently define the alignment of the knee flexion/extension axis during static capture. These were removed during dynamic trials and two retroreflective markers (Ø = 14 mm) were placed bilaterally over the lateral epicondyles of the knee. The participants undertook a number of barefoot walking trials until three were collected in which the ipsilateral foot contacted a force plate during both initial contact and toe off. Patients were tested pre-surgery and nine months post-surgery.

3.2. Data analysis

Raw data were processed in Vicon Nexus by filling marker trajectory gaps using a Woltring quintic spline routine when the gaps were less than 10 frames [25]. Marker trajectories and kinetic data were filtered using a fourth order low pass Butterworth filter with zero lag. A cutoff frequency of 6 Hz and 300 Hz was used for marker trajectories and kinetic data, respectively. The processed data were imported into Polygon Authoring Tool (3.5.1, Vicon, Oxford, UK) to normalise the trials to gait cycle percentage. Moments were normalised to Newton metres per kilogramme of body mass. Discrete kinematic and kinetic variables of the affected knee were processed following data normalisation in Polygon Authoring Tool. Discrete parameters encompassing the maximum, minimum, and range were chosen over continuous waveforms as they have a greater potential to characterise knee gait patterns [20].

3.3. Statistical analysis

Normality of distribution was determined by calculating skewness and kurtosis in order to verify the assumptions of the ANOVA parametric tests in PASW Statistics (Version 18, Chicago, IL, USA). Skewness and kurtosis were converted to z-scores. The resultant z-score was indicative of a normal distribution if the magnitude was <1.96 [21]. A one way repeated measures ANOVA was then undertaken to analyse differences between groups (FB, MB, control) at pre-surgery and nine months post-surgery. Sphericity was assumed if Mauchly's test was not significant (p > 0.05). In data where sphericity was not assumed, the violations were adjusted for by using the Greenhouse–Geisser correction. If the

Table 1
Demographic and anthropometric parameters of the fixed bearing (FB), mobile bearing (MB), and control groups.

	FB		MB		Control		ANOVA		FB–control	MB–control	FB–MB
	Mean	SD	Mean	SD	Mean	SD	F	p	Sig	Sig	Sig
n	8	–	8	–	8	–	–	–	–	–	–
Male	5	–	5	–	5	–	–	–	–	–	–
Female	3	–	3	–	3	–	–	–	–	–	–
Age (years)	59.3	8.8	59.6	7.7	60.5	7	0.046	$p = 0.96$	–	–	–
Height (m)	1.66	0.09	1.7	0.09	1.67	0.12	0.44	$p = 0.65$	–	–	–
Mass (kg)	87.85	16.06	91.21	12.43	72.58	9.43	4.73	*	0.069	*	0.86
BMI (kg/m^2)	31.92	6.8	31.92	6.8	26.06	1.21	3.86	*	0.063	0.064	1
OKS (pre-surgery)	39	7.64	37.42	5.32	–	–	0.018	$p = 0.89$	–	–	–
OKS (three months post-surgery)	25.88	12.18	24.5	9.62	–	–	0.018	$p = 0.89$	–	–	–
OKS (nine months post-surgery)	19.57	5.65	21.14	9.53	–	–	0.018	$p = 0.89$	–	–	–

'OKS' equates to 'Oxford Knee Score'; 'SD' to 'standard deviation'; '*' to 'significant at the 0.05 level'.

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Table 2
Fixed bearing (FB), mobile bearing (MB), and control participant between group differences of spatiotemporal parameters at pre-surgery, three months post-surgery, and nine months post-surgery.

		FB		MB		Control		ANOVA		FB–control			MB–control			FB–MB		
		Mean	SD	Mean	SD	Mean	SD	F	p	Mean dif	SE	p	Mean dif	SE	p	Mean dif	SE	p
Pre-surgery	Cadence (steps/min)	100.55	22.40	89.60	9.64	120.38	14.07	12.72	*	19.83	8.51	0.1	30.78	8.88	*	10.95	9.14	0.74
	Foot off (gait cycle %)	61.17	4.02	60.08	1.49	60.54	1.21	2.76	0.083	–	–	–	–	–	–	–	–	–
	Stride length (m)	1.05	0.15	1.13	0.20	1.30	0.10	12.51	*	0.24	0.078	*	0.17	0.08	0.16	0.077	0.08	1
	Stride time (s)	1.25	0.31	1.32	0.17	1.01	0.11	10.97	*	0.24	0.11	0.11	0.31	0.11	*	0.071	0.12	1
	Gait velocity (m/s)	0.89	0.26	0.87	0.20	1.29	0.11	33.18	*	0.4	0.1	*	0.43	0.11	*	0.021	0.11	1
Nine months post-surgery	Cadence (steps/min)	101.23	16.87	96.3	10.08	120.38	14.07	12.72	*	19.15	7.32	0.05	24.08	7.64	*	4.93	7.87	1
	Foot off (gait cycle %)	63.08	1.79	61.57	0.80	60.54	1.21	2.76	0.083	–	–	–	–	–	–	–	–	–
	Stride length (m)	1.11	0.13	1.23	0.09	1.30	0.10	12.51	*	0.18	0.056	*	0.071	0.06	0.71	0.11	0.06	0.23
	Stride time (s)	1.25	0.25	1.23	0.12	1.01	0.11	10.97	*	0.24	0.089	*	0.22	0.09	0.08	0.017	0.1	1
	Gait velocity (m/s)	1.01	0.21	1.00	0.12	1.29	0.11	33.18	*	0.28	0.08	*	0.29	0.08	*	0.01	0.09	1

'SD' equates to 'standard deviation'; 'Mean dif' to 'mean difference'; 'SE' to 'standard error'; '*' to 'significant at the 0.05 level'.

ANOVA was significant ($p < 0.05$), post-hoc pairwise comparisons using the Bonferroni method for the adjustment of multiple comparisons were undertaken.

4. Results

Axial plane kinematic and kinetic parameters were excluded from the results as no differences were found between all groups.

4.1. Spatiotemporal

At pre-surgery, reductions were found in the FB group when compared to controls in stride length ($F_{1.46, 26.28} = 12.51$; $p < 0.05$) and gait velocity ($F_{1.33, 23.92} = 33.18$; $p < 0.05$) (Table 2). Similar findings were apparent in the MB group with a reduction in gait velocity ($F_{1.33, 23.92} = 33.18$; $p < 0.05$) and cadence ($F_{1.46, 26.21} = 12.72$; $p < 0.05$), and an increase in stride time ($F_{1.27, 22.83} = 10.97$; $p < 0.05$) when compared to controls. No significant differences were observed between FB and MB groups.

The FB group walked with reduced stride length ($F_{1.46, 26.28} = 12.51$; $p < 0.05$), gait velocity ($F_{1.33, 23.92} = 33.18$; $p < 0.05$), and stride time ($F_{1.27, 22.83} = 10.97$; $p < 0.05$) when compared to controls at nine months post-surgery. The MB group derived reductions in cadence ($F_{1.46, 26.21} = 12.72$; $p < 0.05$) and gait velocity ($F_{1.33, 23.92} = 33.18$, $p < 0.05$). No significant differences were observed between FB and MB groups.

4.2. Kinematic

Reductions were found across both FB ($F_{2, 38} = 22.9$; $p < 0.05$) and MB ($F_{2, 38} = 22.9$; $p < 0.05$) groups in sagittal ROM when compared to controls at pre-surgery (Table 3). The MB group was found to exhibit a reduced frontal knee ROM compared to controls ($F_{2, 38} = 9.04$; $p < 0.05$). The MB group was also found to walk with a reduced frontal knee ROM ($F_{2, 38} = 9.04$; $p < 0.05$) than the FB group (FB = 14.92 ± 4.02°; MB = 8.87 ± 4.82°).

The FB ($F_{1.26, 25.82} = 17.51$; $p < 0.05$) and MB ($F_{1.26, 25.82} = 17.51$; $p < 0.05$) groups walked with greater minimum knee flexion angles than controls at nine months post-surgery. The MB group also exhibited a significantly reduced sagittal knee ROM when compared to controls ($F_{2, 38} = 22.9$; $p < 0.05$). No significant differences were observed between FB and MB groups.

4.3. Kinetic

At pre-surgery, the MB group walked with a reduced maximum knee extension moment than controls ($F_{1.31, 23.49} = 10.95$; $p < 0.05$) (Table 4). This finding was replicated in the maximum knee flexion moment ($F_{2, 36} = 8.26$; $p < 0.05$), with a reduction observed when compared to controls. No significant differences were observed between FB and MB prostheses.

At nine months post-surgery, the FB group walked with a greater knee flexion angle at the incidence of the maximum knee extension moment ($F_{1.51, 27.24} = 7.8$; $p < 0.05$), in addition to a reduced maximum knee adduction moment compared to controls ($F_{1.3, 23.48} = 9.2$; $p < 0.05$). Significance was also reached in the MB group, with the patients walking with a reduced maximum knee adduction moment than controls ($F_{1.3, 23.48} = 9.2$; $p < 0.05$). No significant differences were observed between FB and MB groups.

5. Discussion

The aim of this study was to compare the three dimensional knee biomechanics of FB and MB total knee prostheses amid the limited previous findings of benefits of MB implanted knees during walking. Concurrent with the previous research [14–17], few biomechanical differences were found between FB and MB prostheses. The FB and MB groups could not be distinguished following an adequate period of rehabilitation at nine months post-surgery [12,22,23], with no parameter reaching significance in the spatiotemporal, kinematic, and kinetic results.

The most important finding of the study was that there was no difference in the sagittal plane knee kinematics of the MB group when compared to the FB group. Differences have been previously reported between FB and MB prostheses in kinematic parameters during walking [16,17] that provide support for the hypothetical, but largely unsubstantiated, biomechanical advantages of the MB paradigm [5]. The normal knee permits axial rotation, with the lateral femoral condyle contacting anterior to the midline of the tibia in extension [24]. With progressive

Table 3
Fixed bearing (FB), mobile bearing (MB), and control participant between group differences of kinematic parameters at pre-surgery, three months post-surgery, and nine months post-surgery.

		FB		MB		Control		ANOVA		FB–control			MB–control			FB–MB		
		Mean	SD	Mean	SD	Mean	SD	F	p	Mean dif	SE	p	Mean dif	SE	p	Mean dif	SE	p
Pre-surgery	Min knee flexion (°)	12.90	10.24	13.18	10.50	6.18	3.16	17.51	*	6.72	4.38	0.42	7	4.38	0.38	0.27	4.52	1
	Max knee flexion (°)	54.75	10.67	54.77	9.85	64.16	2.74	2.99	0.06	–	–	–	–	–	–	–	–	–
	Sagittal knee ROM (°)	41.85	9.080	41.59	8.38	57.97	3.73	22.9	*	16.13	3.78	*	16.38	3.78	*	0.25	3.91	1
	Max knee abduction (°)	−6.53	14.09	−3.53	10.34	−7.11	7.58	1.98	0.17	–	–	–	–	–	–	–	–	–
	Max knee adduction (°)	8.39	13.53	5.34	11.70	7.41	5.83	4.85	*	0.97	5.51	1	2.07	5.51	1	3.05	5.70	1
	Frontal knee ROM (°)	14.92	4.02	8.87	4.82	14.52	3.39	9.04	*	0.39	2.11	1	5.66	2.11	*	6.05	2.18	*
Nine months post-surgery	Min knee flexion (°)	14.53	5.26	16.99	4.45	6.18	3.16	17.51	*	8.35	2.24	*	10.81	2.24	*	2.46	2.31	0.9
	Max knee flexion (°)	64.01	4.02	63.79	7.75	64.16	2.74	2.99	0.06	–	–	–	–	–	–	–	–	–
	Sagittal knee ROM (°)	49.48	6.62	46.79	9.41	57.97	3.73	22.9	*	8.5	3.55	0.08	11.18	3.55	*	2.68	3.66	1
	Max knee abduction (°)	−13.94	12.94	−11.08	6.57	−7.11	7.58	1.98	0.17	–	–	–	–	–	–	–	–	–
	Max knee adduction (°)	1.82	11.93	−1.64	4.89	7.41	5.83	4.85	*	5.59	4.17	0.59	9.06	4.17	0.13	3.47	4.31	1
	Frontal knee ROM (°)	15.77	7.03	9.43	2.22	14.52	3.39	9.04	*	1.25	2.40	1	5.09	2.40	0.14	6.34	2.47	0.06

'SD' equates to 'standard deviation'; 'Mean dif' to 'mean difference'; 'SE' to 'standard error'; '*' to 'significant at the 0.05 level'.

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Table 4
Fixed bearing (FB), mobile bearing (MB), and control participant between group differences of kinetic parameters at pre-surgery, three months post-surgery, and nine months post-surgery.

		FB		MB		Control		ANOVA		FB–control			MB–control			FB–MB		
		Mean	SD	Mean	SD	Mean	SD	F	p	Mean dif	SE	p	Mean dif	SE	p	Mean dif	SE	p
Pre-surgery	Max knee ext. moment (Nm/kg)	−0.28	0.15	−0.25	0.043	−0.39	0.047	10.95	*	0.11	0.047	0.08	0.14	0.05	*	0.026	0.051	1
	Max knee flx. moment (Nm/kg)	0.54	0.35	0.49	0.29	0.96	0.30	8.26	*	0.42	0.16	0.05	0.47	0.17	*	0.048	0.17	1
	Knee flx. at max ext. moment (°)	13.96	10.28	14.80	10.92	11.00	3.89	7.8	*	2.97	4.46	1	3.8	4.65	1	0.83	4.79	1
	Knee flx. at max flx. moment (°)	26.73	11.59	24.38	8.79	25.52	5.57	0.4	0.61	–	–	–	–	–	–	–	–	–
	Max knee ab. moment (Nm/kg)	−0.13	0.19	−0.06	0.05	−0.11	0.04	0.03	0.98	–	–	–	–	–	–	–	–	–
	Max knee add. moment (Nm/kg)	0.44	0.13	0.40	0.17	0.46	0.13	9.2	*	0.019	0.073	1	0.058	0.076	1	0.039	0.078	1
Nine months post-surgery	Max knee ext. moment (Nm/kg)	−0.38	0.12	−0.34	0.097	−0.39	0.047	10.95	*	0.011	0.047	1	0.058	0.049	0.75	0.047	0.051	1
	Max knee flx. moment (Nm/kg)	0.75	0.40	0.73	0.25	0.96	0.30	8.26	*	0.21	0.17	0.67	0.24	0.18	0.59	0.022	0.18	1
	Knee flx. at max ext. moment (°)	17.65	6.41	17.22	3.60	11.00	3.89	7.8	*	6.65	2.49	*	6.22	2.60	0.08	0.43	2.68	1
	Knee flx. at max flx. moment (°)	27.92	9.50	22.20	4.95	25.52	5.57	0.4	0.61	–	–	–	–	–	–	–	–	–
	Max knee ab. moment (Nm/kg)	−0.10	0.04	−0.13	0.07	−0.11	0.04	0.03	0.98	–	–	–	–	–	–	–	–	–
	Max knee add. moment (Nm/kg)	0.30	0.08	0.26	0.11	0.46	0.13	9.2	*	0.16	0.056	*	0.19	0.059	*	0.038	0.061	1

'SD' equates to 'standard deviation'; 'Mean dif' to 'mean difference'; 'SE' to 'standard error'; '*' to 'significant at the 0.05 level'.

flexion, the lateral femoral condyle translates proportionally to a position that is posterior to the midline of the tibia. The proposed increase of sagittal knee ROM in MB knees is achieved through this femoral roll-back during knee flexion and subsequent internal rotation of the tibia during knee extension [25], similar to the normal knee.

Mockel et al. [16] found that these mechanical advantages elicited a greater mean stance phase knee flexion in MB prostheses when compared to FBs. Further, Kramers de-Quervain et al. [17] detailed an increase in the maximum knee flexion of MB prostheses when compared to FBs. Unfortunately, no pre-operative data were presented for Kramers de-Quervain et al. [17], making it difficult to conclude that the post-surgery differences were representative of a true effect, as differences may have been apparent prior to implantation.

Despite the advantageous findings for MB prostheses, Sosio et al. [15] found no differences in knee flexion at heel contact, maximum knee flexion in stance, maximum knee extension in stance, and maximum knee flexion in swing between FB and MB groups. Tibesku et al. [14] found little mean differences in maximum and ROM in stance and swing, not exceeding that of the 0.5 standard deviation between groups, although the authors did not statistically compare FB and MB groups, but rather analysed the progression from pre-surgery to post-surgery.

A difference was observed at the pre-surgery time point in the current study, with the MB group found to walk with reduced frontal plane knee ROM compared to the FB group at pre-surgery, with both groups otherwise similar. Despite this finding, between-group similarity was compounded with the pre-surgery OKS, with no significant differences between groups (Table 1), and both groups indicative of 'moderate to severe osteoarthritis' (31–40) [26]. The difference in frontal plane ROM was not apparent following surgery, however, suggesting little meaningful difference following rehabilitation.

Although no differences were found between FB and MB groups, refuting the observations of Mockel et al. [16] and Kramers-de Quervain et al. [17], important differences were observed between the FB and MB groups when compared to the controls. Both FB and MB groups walked with a greater minimum knee flexion than controls following surgery, suggesting the presence of a flexion contracture [27]. An increase in knee flexion coupled with the reduction in gait velocity has been suggested to be an associate factor of a 'stiff knee' gait pattern [28].

Interestingly, the suggestion of a flexion contracture was not supported by the kinetic results, with no differences between FB and MB groups in the maximum knee flexion moment when compared to controls. Dorr et al. [29] suggested that reductions in the knee flexion moment are indicative of greater quadriceps and biceps femoris activity. It has been postulated that these mechanisms are adopted to reduce shear forces, or attributed to patterns developed prior to TKR surgery; however, this was not apparent in the current study.

Reductions were found in both FB and MB groups in the maximum knee adduction moment when compared to controls following surgery. Mechanically, reduced knee adduction moments suggest reduced loading of the medial compartment of the knee [1,30]. Reductions in ipsilateral knee loading may invoke greater loading in the contralateral knee, with an unequal loading ratio being an important risk factor for OA progression [31].

Fixed bearing and MB groups also walked slower than controls at pre-surgery and post-surgery time points. The FB group walked with a reduced stride length and increased stride time at post-surgery compared to controls, which was not observed in the MB group. The pre-surgery results suggest that the FB group had a reduced stride length prior to surgery, however, somewhat explaining the significant finding following surgery.

This study has a number of strengths. The addition of pre-surgery testing is imperative in validating post-surgery findings. Although useful, it is difficult to make informed clinical decisions from retrospectively designed studies due to the omission of pre-surgery analyses [15,17]. We also used the same implant manufacturer with the same femoral components, in addition to both prostheses being posterior stabilised with the patella resurfaced, limiting potential confounding factors. The predominant limitation of the current study is that of a small sample size, although comparable to the previous literature [15,17]. A power calculation was undertaken at the investigation outset, which suggested a total sample size of 21, inclusive of the FB, MB, and control groups. We are therefore confident that the results are of sufficient statistical power to distinguish a 'medium' effect among groups [32]. A further limitation is that the study only assessed walking. It is possible that MBs may offer advantages in activities requiring greater knee flexion where a FB prosthesis has a limited ability to rotate.

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Our results suggest that MB prostheses do not offer any biomechanical advantages over FB designs during walking. Indeed, both groups showed findings indicative of a 'stiff knee' gait and decreased medial compartmental loading when compared to controls. Fixed bearing and MB prostheses both differed from controls in six and five parameters at post-surgery, respectively. This suggests that no prosthesis design exhibited conclusive superiority over another with regards to returning normal knee biomechanics.

Conflict of interest statement

A grant was received from DePuy International providing funding for the study. DePuy International approved the concept and design of the research at the investigation outset, although the company did not have input into the analysis and interpretation of the data, or the decision to submit the work for publication.

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Appendix D

Published paper

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VALIDATION OF AN ELECTROGONIOMETRY SYSTEM AS A MEASURE OF KNEE KINEMATICS DURING ACTIVITIES OF DAILY LIVING

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ABSTRACT

Purpose: The increasing use of electrogoniometry (ELG) in clinical research requires the validation of different instrumentation. The purpose of this investigation was to examine the concurrent validity of an ELG system during activities of daily living. **Methods:** A total of 10 asymptomatic participants gave informed consent to participate. A Biometrics SG150 electrogoniometer was directly compared to a 12 camera three-dimensional motion analysis system during walking, stair ascent, stair descent, sit to stand, and stand to sit activities for the measurement of the right knee angle. Analysis of validity was undertaken by linear regression. Standard error of estimate (SEE), standardized SEE (SSEE), and Pearson's correlation coefficient *r* were computed for paired trials between systems for each functional activity. **Results:** The 95% confidence interval of SEE was reasonable between systems across walking (LCI = 2.43°; UCI = 2.91°), stair ascent (LCI = 2.09°; UCI = 2.42°), stair descent (LCI = 1.79°; UCI = 2.10°), sit to stand (LCI = 1.22°; UCI = 1.41°), and stand to sit (LCI = 1.17°; UCI = 1.34°). Pearson's

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correlation coefficient r across walking (LCI = 0.983; UCI = 0.990), stair ascent (LCI = 0.995; UCI = 0.997), stair descent (LCI = 0.995; UCI = 0.997), sit to stand (LCI = 0.998; UCI = 0.999), and stand to sit (LCI = 0.996; UCI = 0.997) was indicative of a strong linear relationship between systems. **Conclusion:** ELG is a valid method of measuring the knee angle during activities representative of daily living. The range is within that suggested to be acceptable for the clinical evaluation of patients with musculoskeletal conditions.

Keywords: Validation; Electrogoniometry; Knee.

INTRODUCTION

Sagittal knee angles have been traditionally measured in non-weight bearing activities, during both supine lying and sitting conditions using manual goniometry.[20] It has been suggested that these methods are dissimilar to sagittal knee kinematics during functional activity.[4] The use of electrogoniometry in the monitoring of sagittal knee kinematics can provide an opportunity to measure everyday functional activities.[8,15,29] This can be undertaken in controlled laboratory environments,[8,15,29] or away from laboratory observation.[28]

The measurement of the sagittal knee angle using manual goniometry is reliant upon the identification of the center of joint rotation.[19] This becomes increasingly difficult during displacement, as the knee translates in both medio-lateral and antero-posterior directions.[26] Three-dimensional motion analysis systems can accurately estimate the center of knee joint rotation,[18] however, they require a fixed laboratory-based camera system,[29] and therefore cannot measure patients outside of a restricted laboratory area. Electrogoniometry systems provide continuous measurement of sagittal knee motion, whilst measuring the angle between two axes defined by the two extremities of the transducer. At the knee joint, the angle is measured between the femoral and tibial segments, rather than relying on the identification of the center of knee joint rotation.[15]

Electrogoniometry is being increasingly used to assess clinical populations.[15,16,21,30] As such, there is a requirement to ascertain the validity of different systems.[8] Electrogoniometry has been previously shown to be a valid measure of knee kinematics.[20] Different electrogoniometers and data acquisition systems are frequently used in electrogoniometry, therefore, generalization of the findings due to electronic component differences across instrumentation cannot be reliably undertaken.[23] Piriyaprasarth *et al.*[18] assessed the reliability of knee joint position using the Biometrics SG150 electrogoniometer. The validity, however, was assessed against a Perspex template using a static protocol, deriving errors of 0.8° to 3.6° over an angular range of 0° to 90°. Maupas *et al.*[12] assessed the validity of the Biometrics SG150 electrogoniometer when attached to a mechanical goniometer, as part of a wider assessment of validity during asymmetric leg activity. The authors reported a mean difference of $1.3° \pm 1.1°$ (range = 0°–4°) when the mechanical goniometer was moved through the range of −160° to +160° measured at 10° increments.

Validation of the Biometrics SG150 electrogoniometer has also been undertaken in humans, with Rowe *et al.*[20] reporting mean differences of $1.5° \pm 2.8°$ during walking when compared to a three-dimensional motion analysis system. This range was suggested by the authors to be acceptable for the clinical evaluation of patients with musculoskeletal disorders.[20] Bronner *et al.*[1] determined the validity of the Biometrics SG150 electrogoniometer across various dancing movements, obtaining validity correlations of $r \geq 0.949$

(SEM ≤ 6.80°) to three-dimensional motion analysis at the knee joint.

To the best of our knowledge, no studies have assessed the validity of the Biometrics SG150 device in humans across a range of activities representative of those undertaken during daily living. The objective of this study was to determine the concurrent validity of the Biometrics SG150 electrogoniometer by comparing sagittal knee angular displacements to a three-dimensional motion analysis system, referred to as the "gold standard" of knee kinematic monitoring,[20] during walking, stair ascent, stair descent, sit to stand, and stand to sit activities. Electrogoniometry has the potential to be used in regular clinical assessments, and is routinely used for research applications. This investigation was undertaken to derive error confidence intervals to scientifically inform practitioners of the validity of a typical electrogoniometer during common ambulatory activities of daily living, in addition to providing reference values to aid data interpretation.

METHOD

Participants

Ethical approval for the study was granted by the Institutional Ethics Committee. A total of 10 asymptomatic male participants were recruited and gave written informed consent prior to participation. Participants had a mean age of 23.1 ± 3.69 years, height of 1.79 ± 0.07 m, mass of 81.57 ± 7.79 kg, and body mass index (BMI) of 25.42 ± 2.21 kg/m^2. Exclusion criteria were current lower extremity injuries that could prevent or restrict the performance of repeated walking, stair ascent, stair descent, sit to stand, and stand to sit movements. Due to the accuracy required for validation purposes, participants were excluded if they had a BMI ≥ 30.00 kg/m^2.

System Preparation

Electrogoniometry System

A twin axis electrogoniometer (SG150, Biometrics, Gwent, UK) was used in the experiment. The electrogoniometer was attached to a portable data logger (8 channel data logger, MIE Medical Research, Leeds, UK) via a preamplifier (MIE Medical Research, Leeds, UK). A sampling frequency of 200 Hz was used to ensure consistency with the motion analysis system, as well as previous research using electrogoniometry.[2,9,18]

Two electronic foot switches (MIE Medical Research, Leeds, UK) were used in the electrogoniometry system as a method of identifying heel strike and toe off events, in addition to enabling synchronization with the motion analysis system. Foot switches were used for level walking, stair ascent, and stair descent in which heel strike and toe off events occurred. Sit to stand and stand to sit trials began with the participant balancing on the contralateral leg with the ipsilateral leg held above the force plate, and then placing the ipsilateral leg in contact with the force plate to enable synchronization.

During electrogoniometer attachment, participants were asked to stand in the anatomical position, with the knees in full extension. The anatomical line was marked between the greater trochanter of the femur and the lateral epicondyle. The same protocol was undertaken for the shank, with the line between the lateral epicondyle and the lateral malleolus identified and marked (see Fig. 1). Double sided hypoallergenic tape was used to attach the endplates to the skin. Microporous surgical tape was applied perpendicular to the endplates to secure attachment.

The live data preview function in MyoDat (6.59.0.8260, MIE Medical Research, Leeds, UK), the instrumentation set-up and analysis software for the data logger, was used to observe the real time output of the electrogoniometer and foot

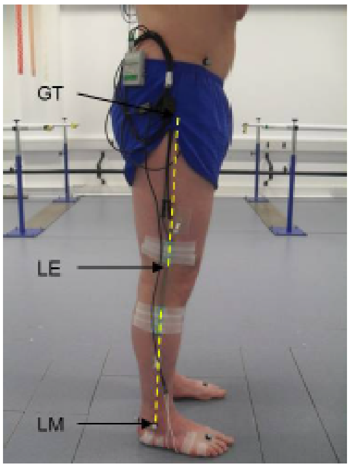

Fig. 1 Set-up of the retroreflective markers and the components of the electrogoniometry system on a participant before static calibration in the motion analysis system. At this point, markers were not placed on the knee. Lines denote the anatomical lines of the femur and shank. GT = greater trochanter; LE = lateral epicondyle; LM = lateral malleolus.

switches. Each participant was asked to flex and extend their knee throughout their full range of motion (ROM), as well as placing their ipsilateral forefoot and heel in contact with the ground to verify correct operating function of both instruments.

Three-Dimensional Motion Analysis System

A 12 camera three-dimensional motion analysis system (Vicon MX, Oxford, UK) was calibrated through a standard dynamic protocol using a five marker calibration wand (Vicon, Oxford, UK). The calibration was accepted when all 12 cameras (T20, Vicon, Oxford, UK) exhibited an image error of < 0.2 mm. Participants had their height and mass taken, along with bilateral leg length, and knee and ankle widths in order to fit the participant's specific dimensions to the lower body "Plug in Gait" model (Vicon, Oxford, UK). A total of 14 retroreflective markers (Ø = 14 mm) were placed bilaterally over anatomical landmarks on the lower body in line with the recommendations of the system manufacturer. These locations were the anterior superior iliac spine, posterior superior iliac spine, lateral distal third of the thigh, lateral distal third of the shank, lateral malleolus, heel on the calcaneous, and the head of the second metatarsal. Kinematic data were subsequently captured at 200 Hz into Vicon Nexus (1.7.1, Vicon, Oxford, UK).

Four force plates (OR6-7, AMTI, Watertown MA, USA) were embedded within a 7 m walkway in the center of the calibrated volume. Four amplifiers (MiniAmp MSA-6, AMTI, Watertown MA, USA) were used to amplify the signal into Nexus at a gain of 1000, with kinetic data captured at 1000 Hz.

The experimental set-up of the retroreflective markers and the components of the electrogoniometry system prior to static calibration in the motion analysis system are depicted in Fig. 1 Two knee alignment devices [(KADs) Vicon, Oxford, UK)] were then placed bilaterally over the medial and lateral epicondyles to independently define the alignment of the knee flexion/extension axis. Following data capture of a static trial, the KADs were removed and two retroreflective markers (Ø = 14 mm) were placed bilaterally over the lateral epicondyles of the knee.

Protocol

The participants undertook a number of walking trials until three were collected in which the right foot made contact with a force plate during both heel strike and toe off events. Three stair ascent trials starting with the right foot were then performed on a custom built stair rig constituting three steps (width = 630 mm; tread = 270 mm; height = 200 mm), with the first step being a force plate (MC818, AMTI, Watertown MA, USA). Whilst standing at the top of the stair rig, participants then undertook three stair descent trials starting with the right foot such that their right foot landed on the force plate. Three sit to stand trials from an orthopedic stool (Nottingham Rehab Supplies, Nottingham, UK) were then performed, with the stool kept at a consistent height of 560 mm. During the sit to stand movement, participants were instructed to cross their arms, so that the upper arm was parallel to the floor in the sagittal plane to avoid marker occlusion. Three stand to sit trials were then performed.

Data Analysis

Three-Dimensional Motion Analysis System

Right heel strike and toe off events in walking and stair ascent were determined by the vertical component of the ground reaction force (vGRF). Marker trajectories in *x*-, *y*-, and *z*- axes were used to identify the initial heel strikes and toe offs in stair descent due to the fixed position of the step force plate at the bottom of the stair rig. Sit to stand and stand to sit trials were also determined by the onset of the vGRF in the ipsilateral leg.

Trials were processed in Vicon Nexus by filling marker trajectory gaps in the data using a Woltring quintic spline routine when the gaps were < 10 frames.[31] Longer gaps were filled using a pattern fill function, adopting the trajectory of a marker with a similar displacement trail. Marker trajectories and kinetic data were filtered using a fourth-order low pass Butterworth filter with zero lag. A cut off frequency of 6 and 300 Hz was used for marker trajectories and kinetic data, respectively. The dynamic gait model was subsequently applied to retrieve the right sagittal knee angular displacement trace.

Electrogoniometry System

Data from the electrogoniometry system were uploaded into MyoDat and exported into Microsoft Excel (Microsoft, Redmond, WA, USA) where they were identified from the relating foot switch output. The trials were then imported into MATLAB (R2007b, MathsWorks, Natick, MA, USA) and were filtered using a low pass finite impulse response filter.

Combined

An analysis of validity by linear regression was undertaken using a spreadsheet developed by Hopkins.[5] The standard error of estimate (SEE), the magnitude of error expressed as a standard deviation between systems, was derived from the analysis spreadsheet. This parameter has been suggested for use in validity studies,[6] and has been used previously as an indicator of error in a validation assessment.[22] Standardization was undertaken by dividing the SEE by the standard deviation of the motion analysis data set to obtain the standardized SEE (SSEE). The SSEE was interpreted using a modified Cohen scale.[7] Predicted residual sums of squares (PRESS statistic) was used to calculate the new prediction error of a potential participant drawn randomly from the same population. Pearson's correlation coefficient *r* was derived to depict the linear relationship between the electrogoniometer and motion analysis system throughout the displacement cycles of walking, stair ascent, stair descent, sit to stand, and stand to sit. Data were input into the linear regression analysis for both systems in raw format sampled at 200 Hz, with no extrapolation undertaken. Specific gait and movement cycles were the same numerical length for both systems within trials.

RESULTS

A representative example of the initial raw data excursion, prior to linear regression, is presented in Fig. 2. Walking produced a Pearson's correlation coefficient r of 0.987 (LCI = 0.983; UCI = 0.990),

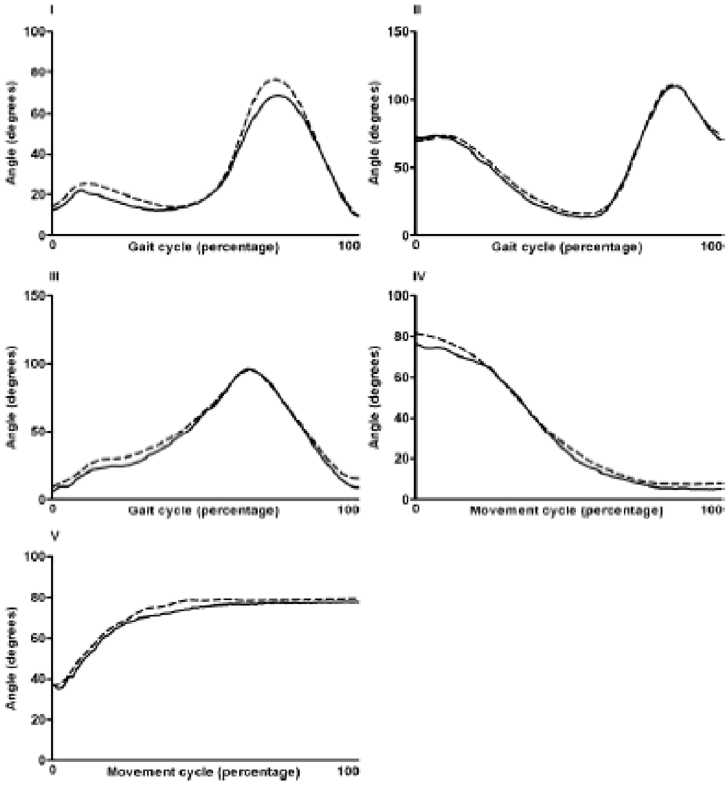

Fig. 2 Representative trace of the right sagittal knee angular displacement as the initial output of the electrogoniometry (–) and motion analysis (- -) systems in one participant across one trial in level walking (I), stair ascent (II), stair descent (III), sit to stand (IV), and stand to sit (V).

which was the weakest relationship amongst the five activities. Stair ascent (LCI = 0.995; UCI = 0.997), stair descent (LCI = 0.995; UCI = 0.997), sit to stand (LCI = 0.998; UCI = 0.999), and stand to sit (LCI = 0.996; UCI = 0.996) all produced correlations of > 0.995 (see Table 1).

Level walking produced the greatest SEE (2.65°; LCI = 2.43°; UCI = 2.91°) across the five activities, although the magnitude of the SSEE was described as "trivial" (0.15; LCI = 0.14; UCI = 0.17) (see Table 2). The smallest SEE was observed

Table 1 Pearson's Correlation Coefficient *r* Depicting the Linear Relationship Between the Electrogoniometer and the Motion Analysis System During Walking, Stair Ascent, Stair Descent, Sit to Stand, and Stand to Sit Activities Across 10 Participants.

	Pearson's Correlation Coefficient *r*	95% Confidence Interval	
Walking	0.987	0.983	0.990
Stair ascent	0.996	0.995	0.997
Stair descent	0.996	0.995	0.997
Sit to stand	0.998	0.998	0.999
Stand to sit	0.997	0.996	0.997

Table 2 SEE and SSEE Between the Electrogoniometer and the Motion Analysis System During Walking, Stair Ascent, Stair Descent, Sit to Stand, and Stand to Sit Activities Across 10 Participants. A Modified Cohen Scale Gives Interpretation of the Magnitude of the Standardised Error. < 0.2= Trivial; 0.2–0.6 = Small; 0.6–1.2 = Moderate; 1.2–2 = Large; > 2 = Very Large (24).

	SEE (°)	95% Confidence Interval (°)		SSEE	95% Confidence Interval (°)		Modified Cohen's *d*	PRESS Error (°)
Walking	2.65	2.43	2.91	0.15	0.14	0.17	Trivial	2.66
Stair ascent	2.24	2.09	2.42	0.08	0.08	0.09	Trivial	2.25
Stair descent	1.93	1.79	2.10	0.08	0.08	0.09	Trivial	1.94
Sit to stand	1.30	1.22	1.41	0.06	0.05	0.06	Trivial	1.31
Stand to sit	1.25	1.17	1.34	0.07	0.07	0.08	Trivial	1.25

in the stand to sit movement (1.25°; LCI = 1.17°; UCI = 1.34°), with the displacement producing a SSEE interpreted as "trivial" (0.07; LCI = 0.07; UCI = 0.08). Stair ascent produced a greater error (2.24°; LCI = 2.09°; UCI = 2.42°) than that of stair descent (1.93°; LCI = 1.79°; UCI = 2.10°), with sit to stand similar to that of stand to sit (1.30°; LCI = 1.22°; UCI = 1.41°). The PRESS error was subsequently greatest in level walking (2.66°), and smallest in stand to sit (1.25°). If a participant was drawn randomly from the same population, the linear regression model can be generalized to derive a SEE of 1.88° between the electrogoniometer and motion analysis system across the five activities examined.

DISCUSSION

The aim of this study was to determine the concurrent validity of the Biometrics SG150 electrogoniometer during activities of daily living in order to present error confidence intervals for practitioners using the instrumentation. The device was compared to three-dimensional motion analysis, a technique deemed accurate,[13] and when applied, capable of measuring knee biomechanics to a high degree of precision.[14] In addition, motion analysis has been described as the "gold standard" for knee kinematic measurement during previous electrogoniometry validation.[20]

The SEE, which was the magnitude by which the electrogoniometer output differed from the motion analysis system output for any given participant over an activity displacement cycle, was found to range from 1.25° during stand to sit to 2.65° in walking. The 95 % confidence interval of the SEE was found to be greatest in walking (2.43–2.91°), and subsequently lowest during stand to sit (1.17–1.34°). Measurement error can arise from a combination of the electrogoniometer, the researcher, or the participant who is being measured.[25] The magnitude of error in this investigation coincides with that of previous studies,[9,20] with Rowe *et al.*[20] presenting differences of 1.5 ± 2.8° during walking. In the current investigation, the upper 95% confidence error limit of walking was within the range suggested by Rowe *et al.*[20] to be valid for clinical use. In an effort to reduce the measurement error, Rowe *et al.*[20] mounted the endplates of the electrogoniometer upon plastic strips, with a view to reducing skin motion artifacts by avoiding direct instrument to skin contact. Foam blocks were also used to reduce the abduction and adduction angulation at the knee in order to attach the instrument in a straight configuration. In the current investigation, mounting of the electrogoniometer directly onto the skin was undertaken with a view to examining the validity of an attachment procedure that could be used with increased time efficiency and a reduced degree of difficulty, as recommended by the manufacturer, and also more suited to applied use. It is perhaps surprising, therefore, that a greater magnitude of error was not established in the current investigation due to the methodological differences compared to Rowe et al.[20] Indramohan et al.,[8] however, also found that their results were unaffected when attaching the electrogoniometer directly onto the skin in a study validating a data logger for use with electrogoniometers. These findings suggest that accurate data can be obtained when the electrogoniometer is attached directly onto the skin, although a meticulous protocol must be followed to minimize error. This provides support for the use of the attachment procedure described in the current investigation in applied settings where preparation time is often limited. The results of current investigation and Rowe et al.[20] suggest that reasonable errors are derived when using electrogoniometry, regardless of attachment procedure.

The mean linear relationship between the electrogoniometer and motion analysis system was found to be very high across walking, stair ascent, stair descent, sit to stand, and stand to sit activities, ranging from 0.987 in walking to 0.998 during sit to stand. These findings were similar to a previous validation report by Bronner et al.[1] who described correlations of $\geq$ 0.949 between an electrogoniometer and motion analysis system when measuring the sagittal knee angle. A similar magnitude of Pearson's correlation coefficient r was observed, although Bronner et al.[1] found a slightly reduced magnitude than that presented in the current investigation. A potential explanation for this difference is that 10 dancing movements were assessed in advanced level collegiate dancers. Dancing movements are often performed at joint extremes,[1] and therefore likely to assume greater magnitudes of displacement and velocity than those seen during walking, stair ascent, stair descent, sit to stand, and stand to sit displacements. Electrogoniometry has been found to display reduced accuracy at motion extremes at the wrist,[10] knee,[20] and during laboratory investigation.[23]

A potential limitation of the current investigation is the effect of soft tissue artifact inaccuracies often associated with three-dimensional motion analyses.[3,11] These errors originate from movement or deformation of the subcutaneous tissues associated with muscular contractions, skin movement, and inertial effects.[17] To reduce the effect of soft tissue artifact errors, participants were excluded if they had a BMI of $\geq 30\,\mathrm{kg/m^2}$. It was hypothesized that participants classified as obese, from the guidelines reported by the World Health Organization,[32] would have an increased subcutaneous tissue layer and therefore be susceptible to greater skin translation during displacement. In the current investigation, retroreflective markers were attached to bony anatomical landmarks, where typically, the thickness of the subcutaneous layer is considerably reduced. This, coupled with the exclusion criteria at the investigation outset, suggests that the measured angular displacements were likely to reflect true knee movement across walking, stair ascent, stair descent, sit to stand, and stand to sit activities. A further limitation is that only young male participants were studied. Care must be taken, therefore, when generalizing the results to other populations, in particular, older symptomatic populations that may be indicative of greater ambulatory variability.

It can be concluded that the Biometrics SG150 electrogoniometer displays errors that are deemed acceptable for the clinical evaluation of patients with musculoskeletal disorders. The instrument is valid when measuring sagittal knee angular displacements during walking, stair ascent, stair descent, sit to stand, and stand to sit activities of daily living. Due to the increasing clinical regard for electrogoniometry, future work should assess the validity of specific symptomatic populations to optimize the scientific rigor of clinical decisions in order to provide the best evidence-based patient care.

ACKNOWLEDGMENTS

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Appendix E

Published abstract

Title: Three dimensional gait analysis of fixed bearing and mobile bearing total knee prostheses during stair descent
Authors: Urwin SG, Kader DF, St Clair Gibson A, Caplan N, Stewart S
Conference: British Association for Surgery of the Knee (BASK), Leeds, UK, 2013

We aimed to investigate whether mobile bearing (MB) prostheses offer functional advantages over fixed bearing (FB) designs during stair descent in a prospective randomised comparative study. Sixteen patients undergoing primary unilateral total knee replacement surgery were randomised to receive either a FB (n = 8) or MB (n = 8) total knee prosthesis. Eight age and gender matched controls underwent the same protocol on one occasion. A 12 camera Vicon system integrated with a force plate on a stair rig was used. Participants were tested at three and nine months post-surgery. The MB group descended with a significantly greater ($p < 0.05$) foot off % than the FB group and controls at three months post-surgery, but not at nine months post-surgery (FB = 65.75 ±3.48%; MB = 75.53 ±6.19%; control = 63.39 ±1.93%). The MB group descended with significantly reduced maximum knee flexion (FB = 93.2 ±4.69°; MB = 83.05 ±2.76°; control = 95.42 ±4.24°) and sagittal range of motion (FB = 73.08 ±4.10°; MB = 59.78± 6.89°; control = 85.53± 4.83°) than the FB group and controls at three months post-surgery, but not at nine months post-surgery. We can conclude that following an adequate period of rehabilitation, no significant differences were observed between FB and MB total knee prostheses. No functional advantages, therefore, were exhibited by MB knees.

Appendix F

Published abstract

VALIDATION OF AN ELECTROGONIOMETRY SYSTEM AS A MEASURE OF KNEE KINEMATICS DURING ACTIVITIES OF DAILY LIVING

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INTRODUCTION

The use of electrogoniometry (ELG) in the monitoring of sagittal knee joint kinematics can provide an opportunity to measure everyday functional activities [1,2]. This can be undertaken in controlled laboratory environments, or away from clinical observation [3]. ELG is being increasingly used to assess clinical populations, as such, there is a requirement to ascertain the validity of different systems. No authors appear to have assessed the validity of the Biometrics SG150 device in humans across a range of functional activities representative of those undertaken during daily living. The objective of this study was to determine the concurrent validity of the Biometrics SG150 electrogoniometer by comparing intersegmental knee angular displacements to a three dimensional motion analysis system (MA) during walking, stair ascent, stair descent, a sit to stand task, and a stand to sit task.

METHODS

Ten asymptomatic male participants were recruited. Participants had a mean age of 23.1yrs±3.69yrs, height of 1.79m±0.07m, mass of 81.57kg±7.79kg, and body mass index (BMI) of 25.42kg/m^2±2.21kg/m^2 and were free from lower extremity injury.

A 12 camera MA system (Vicon MX, Oxford, UK) was calibrated through a standard dynamic protocol. Participants had 16 retroflective markers placed over anatomical landmarks in line with the lower body Plug in Gait model recommendations (Vicon, Oxford, UK).

A Biometrics SG150 electrogoniometer (Biometrics, Gwent, UK) was placed over the lateral border of the right knee on the anatomical line of the greater trochanter, lateral epicondyle, and lateral malleolus. Electronic foot switches were attached to the forefoot and heel to synchronize the ELG and MA system in analysis.

Participants undertook multiple walking trials until three were collected that coincided with a heel strike on a force plate. Three stair ascent and stair descent trails were performed on a stair rig with a force plate built into the first step. Participants then performed three sit to stand and stand to sit trials onto an orthopaedic stool whilst standing bilaterally on two force plates. Stool height was kept at a consistent height of 560mm during the performance of both sit to stand and stand to sit trials.

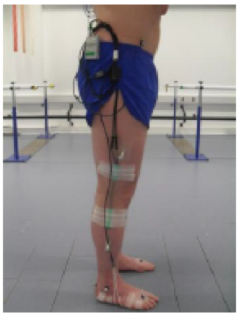

Figure 1: Set-up of the ELG system and retroflective markers required for MA in one participant.

Analysis of validity by linear regression was undertaken. The typical error and Pearson's correlation coefficient r were computed for three paired trials between systems for each functional activity.

RESULTS AND DISCUSSION

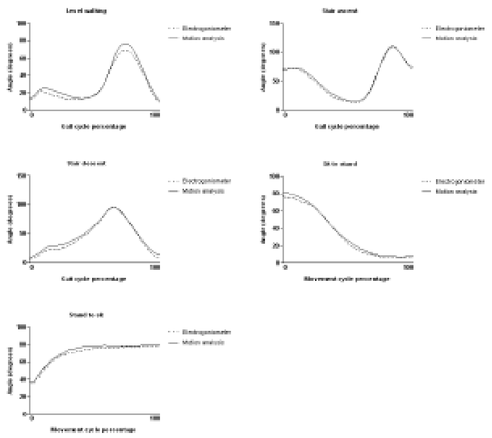

Figure 2: Representative raw data trace of one participant between the ELG and MA systems across walking, stair ascent, stair descent, sit to stand, and stand to sit displacements for the right knee angle.

The mean typical error of estimate, which was the typical magnitude by which the ELG output differed from the MA system output for any given participant over an activity displacement cycle, was found to be 1.87° across walking, stair ascent, stair descent, sit to stand, and stand to sit (Table 1). With 95% statistical confidence, the typical error in this investigation was between 1.74° and 2.04°. Standardisation of this error across all activities produced a 'Trivial' difference of 0.09 between the ELG and MA systems interpreted using a modified Cohen scale.

The mean linear relationship between the ELG and MA system was found to be very high ($r = 0.995$) across walking, stair ascent, stair descent, sit to stand, and stand to sit (Table 1). This was found to be similar to a previous validation report that described correlations of $r \geq 0.949$ between an ELG and MA system when measuring the knee angle in ten dancing movements [4].

CONCLUSION

ELG is a valid method of measuring the knee angle during activities representative of daily activity. The range is within that suggested to be acceptable for the clinical evaluation of patients with musculoskeletal conditions [2].

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The authors would like to thank De Puy International for finding this investigation.

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Table 1: Raw typical error of estimate and Pearson's correlation coefficient *r* between the ELG and MA systems.

	Typical error (°)	95% confidence interval		Pearson's *r*	95% confidence interval	
Walking	2.65	2.43	2.91	0.987	0.983	0.990
Stair ascent	2.24	2.09	2.42	0.996	0.995	0.996
Stair descent	1.93	1.79	2.10	0.996	0.995	0.996
Sit to stand	1.30	1.22	1.41	0.998	0.998	0.998
Stand to sit	1.25	1.17	1.34	0.997	0.996	0.997
Mean	1.87	1.74	2.04	0.995	0.993	0.995
SD	0.60	0.55	0.67	0.004	0.006	0.003

Appendix G

Published abstract

Title: Long term monitoring of knee flexion angle: A spectrum analysis
Authors: Urwin SG, Kader DF, St Clair Gibson A, Caplan N, Stewart S
Conference: 2nd International Conference of Ambulatory Monitoring of Physical Activity and Movement, Glasgow, UK, 2011

Joint range of movement (ROM) of clinical groups is routinely measured in laboratory and clinical settings. Due to potential behaviour modification during scientific or clinical consultations, this may not accurately reflect normal ROM over an extended period. The objective of this investigation was to therefore obtain normative data of knee flexion angular displacements during seven hours of normal everyday activity in asymptomatic participants for comparative use in clinical trials. A Flexible electrogoniometer (SG150, Biometrics, UK) was used to monitor right knee flexion angular displacement in the sagittal plane, using a portable data logger (MIE Medical Research, UK), sampled at 200Hz. The device was attached to the skin over the lateral border of the knee, in line with the anterior superior iliac spine and the lateral malleolus, equidistant between the anterior and posterior borders of the thigh and shank. Participants (n = 10) were fitted with the system at 8am in the laboratory, and subsequently asked to return seven hours later in order to obtain a representative sample of their normal ROM during a cross-section of an average day, away from laboratory observation. Mean findings suggest that the largest percentage (27.30%) of the seven hour monitoring period was spent with the knee flexed between $\geq 20^\circ\ \theta < 40^\circ$ of flexion. The percentages across the ranges were as follows for angular displacement: $\geq -10^\circ\ \theta < 0^\circ$ = 10.98% ± 9.24%, $\geq 0^\circ\ \theta < 10^\circ$ = 12.45% ± 15.74%, $\geq 10^\circ\ \theta < 20^\circ$ = 8.48% ± 4.54%, $\geq 20^\circ\ \theta < 30^\circ$ = 15.31% ± 6.05%, $\geq 30^\circ\ \theta < 40^\circ$ = 11.98% ± 6.09%, $\geq 40^\circ\ \theta < 50^\circ$ = 10.89% ± 4.73%, $\geq 50^\circ\ \theta < 60^\circ$ = 9.55% ± 4.56%, $\geq 60^\circ\ \theta < 70^\circ$ = 8.76% ± 6.24%, $\geq 70^\circ\ \theta < 80^\circ$ = 5.64% ± 2.85%, $\geq 80^\circ\ \theta < 90^\circ$ = 3.89% ± 4.63%, $\geq 90^\circ\ \theta < 100^\circ$ = 2.24% ± 4.06%, $\geq 100^\circ\ \theta < 110^\circ$ = 0.31% ± 0.78%. The mean angular velocity spectrum showed that for 43.23% ± 1.71% of the monitoring time participants flexed their knee between 0 – 100°/s, with the mean extension angular velocity (42.77% ± 2.48%) also between 0 – 100°/s. This study has shown that asymptomatic participants spend the greatest duration of time with the knee flexed between $20^\circ \leq \theta < 40^\circ$ of flexion; a range that satisfies the increments of all activity movement cycles. Current research is on-going using this method to compare clinical populations in the outpatient setting for use as an objective rehabilitation monitoring tool in total knee replacement patients.

[1] Rowe PJ, Myles CM, Walker C, Nutton RW. Knee joint kinematics in gait and other functional activities measured using flexible electrogoniometry: how much knee motion is sufficient for normal daily life? Gait and Posture 2000; 12: 143-155.

Appendix H

MATLAB code

Counting the magnitude of numbers within a range in MATLAB

$\boldsymbol{counter} = \mathbf{0}$;
$\boldsymbol{for}\ \boldsymbol{i} = \mathbf{1}{:}\ \boldsymbol{length}(\boldsymbol{d})$:
$\boldsymbol{if}(\boldsymbol{d}\ \boldsymbol{i} => x)\ \&\&\ (\boldsymbol{d}\ \boldsymbol{i} < y)$;
$\boldsymbol{counter} = \boldsymbol{counter} + \mathbf{1}$;
$\boldsymbol{end}$;
$\boldsymbol{end}$;
$\boldsymbol{counter}$

- *'counter' = returns the number of values in a specified range*
- *'length' = length of d (data)*
- *'d' = array containing the post-filtered right knee angular displacement data*
- *'x' = first increment value of the category, i.e. -10°*
- *'y' = second increment value of the category, i.e. 0°*

Differentiation of knee angular displacement data in MATLAB

$\boldsymbol{velo} = \boldsymbol{diff}(\boldsymbol{d}) * \mathbf{200}$

- *'velo' = array where the product of the differentiation was input*
- *'d' = array containing the post-filtered right knee angular displacement data*
- *'diff' = computes the differences between adjacent elements of d*
- *'200' = the sampling frequency used in the electrogoniometry system*

Appendix I

Control participant screening questionnaire

northumbria
UNIVERSITY

Participant Screening Questionnaire

Participant ID ________________

please tick for 'Yes'
cross for 'No'

Are your lower limbs usually free from pain?	☐
Are you able to walk without a support?	☐
Are you able to walk for 30 minutes or more without difficulty?	☐
Do you walk with a limp?	☐
Can you put on socks or shoes without difficulty?	☐
Can you use stairs without using a railing?	☐
Are you able to use public transport?	☐
Can you sit comfortably in a chair for an hour?	☐

Appendix J

Typical error and standardised typical error of the spatiotemporal parameters at pre-surgery in Chapter 4

Table Appendix J – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of spatiotemporal parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Walking																		
Cadence (steps/min)	9.01	5.95	18.3	0.38	0.25	0.77	4.88	2.92	14.0	0.39	0.23	1.12	4.09	2.55	10.0	0.29	0.18	0.70
Foot off (gait cycle %)	2.17	1.13	13.6	0.53	0.28	3.33	0.47	0.31	0.95	0.25	0.17	0.51	0.85	0.56	1.74	0.63	0.42	1.28
Stride length (m)	0.06	0.04	0.11	0.38	0.25	0.77	0.05	0.03	0.11	0.24	0.16	0.49	0.07	0.05	0.15	0.66	0.44	1.34
Stride time (s)	0.21	0.14	0.42	0.56	0.37	1.14	0.06	0.04	0.12	0.34	0.22	0.69	0.03	0.02	0.07	0.30	0.20	0.62
Gait velocity (m/s)	0.09	0.05	0.25	0.35	0.21	1.00	0.06	0.04	0.12	0.26	0.17	0.52	0.09	0.06	0.18	0.70	0.46	1.43
Mean	-	-	-	0.44	0.27	1.40	-	-	-	0.30	0.19	0.67	-	-	-	0.52	0.34	1.07
SD	-	-	-	0.10	0.06	1.09	-	-	-	0.07	0.03	0.27	-	-	-	0.20	0.14	0.38
Stair ascent																		
Cadence (steps/min)	3.61	2.16	10.4	0.15	0.09	0.42	N/A	N/A	N/A	N/A	N/A	N/A	2.46	1.59	5.42	0.13	0.08	0.29
Foot off (gait cycle %)	7.59	4.54	21.8	0.97	0.58	2.78	N/A	N/A	N/A	N/A	N/A	N/A	1.43	0.92	3.14	0.48	0.31	1.05
Stride length (m)	0.06	0.03	0.16	0.84	0.50	2.42	N/A	N/A	N/A	N/A	N/A	N/A	0.04	0.02	0.08	0.70	0.45	1.55
Stride time (s)	0.14	0.09	0.42	0.19	0.11	0.54	N/A	N/A	N/A	N/A	N/A	N/A	0.03	0.02	0.07	0.14	0.09	0.31
Gait velocity (m/s)	0.05	0.03	0.13	0.27	0.16	0.78	N/A	N/A	N/A	N/A	N/A	N/A	0.09	0.06	0.18	0.70	0.46	1.43
Mean	-	-	-	0.48	0.29	1.39	-	-	-	N/A	N/A	N/A	-	-	-	0.43	0.28	0.93
SD	-	-	-	0.39	0.23	1.12	-	-	-	N/A	N/A	N/A	-	-	-	0.28	0.19	0.60
Stair descent																		
Cadence (steps/min)	5.70	2.97	35.8	0.29	0.15	1.81	N/A	N/A	N/A	N/A	N/A	N/A	8.26	5.46	16.80	0.54	0.35	1.09
Foot off (gait cycle %)	10.56	6.33	30.3	1.06	0.64	3.05	N/A	N/A	N/A	N/A	N/A	N/A	1.50	0.99	3.05	0.68	0.45	1.38
Stride length (m)	0.03	0.02	0.07	0.49	0.29	1.41	N/A	N/A	N/A	N/A	N/A	N/A	0.03	0.02	0.05	0.57	0.38	1.16
Stride time (s)	0.28	0.17	0.81	0.52	0.31	1.50	N/A	N/A	N/A	N/A	N/A	N/A	0.12	0.08	0.24	0.56	0.37	1.13
Gait velocity (m/s)	0.05	0.03	0.14	0.40	0.24	1.16	N/A	N/A	N/A	N/A	N/A	N/A	0.06	0.04	0.12	0.66	0.44	1.35
Mean	-	-	-	0.55	0.33	1.79	-	-	-	N/A	N/A	N/A	-	-	-	0.60	0.40	1.22
SD	-	-	-	0.30	0.19	0.74	-	-	-	N/A	N/A	N/A	-	-	-	0.06	0.04	0.13

Appendix K

Pearson's correlation coefficient *r* and the intraclass correlation of the spatiotemporal parameters at pre-surgery in Chapter 4

Table Appendix K – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of spatiotemporal parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
Walking																		
Cadence (steps/min)	0.876	0.448	0.977	0.904	0.597	0.980	0.894	0.057	0.993	0.878	0.153	0.972	0.945	0.574	0.994	0.939	0.637	0.986
Foot off (gait cycle %)	0.843	0.341	0.971	0.755	-3.121	0.950	0.950	0.741	0.991	0.960	0.814	0.992	0.620	-0.151	0.922	0.679	0.023	0.926
Stride length (m)	0.906	0.555	0.983	0.903	0.593	0.980	0.945	0.717	0.990	0.963	0.828	0.992	0.580	-0.210	0.910	0.64	-0.040	0.920
Stride time (s)	0.717	0.025	0.945	0.757	0.182	0.946	0.914	0.587	0.984	0.924	0.671	0.984	0.918	0.603	0.985	0.940	0.733	0.988
Gait velocity (m/s)	0.936	0.308	0.996	0.904	0.301	0.978	0.934	0.672	0.988	0.958	0.806	0.991	0.574	-0.219	0.911	0.583	-0.136	0.900
Mean	0.856	0.335	0.974	0.845	-0.290	0.967	0.927	0.555	0.989	0.937	0.654	0.986	0.727	0.119	0.944	0.756	0.243	0.944
SD	0.085	0.199	0.019	0.081	1.593	0.017	0.023	0.284	0.003	0.036	0.287	0.009	0.187	0.429	0.042	0.171	0.408	0.040
Stair ascent																		
Cadence (steps/min)	0.983	0.763	0.999	0.999	0.993	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.999	0.991	1.000	0.991	0.951	0.999
Foot off (gait cycle %)	0.067	-0.867	0.896	0.096	-0.776	0.842	N/A	N/A	N/A	N/A	N/A	N/A	0.789	0.088	0.967	0.849	0.356	0.972
Stride length (m)	0.298	-0.793	0.934	0.423	-0.592	0.919	N/A	N/A	N/A	N/A	N/A	N/A	0.545	-0.353	0.920	0.602	-0.183	0.918
Stride time (s)	0.972	0.625	0.998	0.998	0.983	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.998	0.989	1.000	0.990	0.943	0.998
Gait velocity (m/s)	0.960	0.505	0.997	0.992	0.928	0.999	N/A	N/A	N/A	N/A	N/A	N/A	0.570	-0.220	0.910	0.580	-0.140	0.900
Mean	0.656	0.047	0.965	0.702	0.307	0.952	N/A	N/A	N/A	N/A	N/A	N/A	0.780	0.299	0.959	0.802	0.385	0.957
SD	0.440	0.806	0.047	0.420	0.908	0.071	N/A	N/A	N/A	N/A	N/A	N/A	0.221	0.651	0.043	0.202	0.555	0.046
Stair descent																		
Cadence (steps/min)	0.975	0.661	0.998	0.953	-0.269	0.994	N/A	N/A	N/A	N/A	N/A	N/A	0.719	0.029	0.945	0.783	0.245	0.953
Foot off (gait cycle %)	-0.125	-0.907	0.851	-0.186	-0.867	0.737	N/A	N/A	N/A	N/A	N/A	N/A	0.542	-0.263	0.902	0.614	-0.089	0.909
Stride length (m)	0.765	-0.361	0.983	0.921	0.432	0.991	N/A	N/A	N/A	N/A	N/A	N/A	0.708	0.006	0.942	0.749	0.166	0.944
Stride time (s)	0.916	0.174	0.995	0.898	0.317	0.989	N/A	N/A	N/A	N/A	N/A	N/A	0.766	0.133	0.955	0.762	0.194	0.947
Gait velocity (m/s)	0.916	0.174	0.995	0.962	0.690	0.996	N/A	N/A	N/A	N/A	N/A	N/A	0.563	-0.235	0.908	0.638	-0.050	0.915
Mean	0.689	-0.052	0.964	0.710	0.061	0.941	N/A	N/A	N/A	N/A	N/A	N/A	0.660	-0.066	0.930	0.709	0.093	0.934
SD	0.462	0.599	0.064	0.501	0.626	0.114	N/A	N/A	N/A	N/A	N/A	N/A	0.100	0.174	0.024	0.077	0.152	0.020

Appendix L

Typical error and standardised typical error of the spatiotemporal parameters at three months post-surgery in Chapter 4

Table Appendix L – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of spatiotemporal parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
<u>Walking</u>																		
Cadence (steps/min)	13.9	9.20	28.3	0.69	0.45	1.40	5.32	3.32	13.1	0.47	0.29	1.15	4.09	2.55	10.0	0.29	0.18	0.70
Foot off (gait cycle %)	2.61	1.72	5.30	0.95	0.63	1.94	1.70	1.06	4.16	0.66	0.41	1.63	0.85	0.56	1.74	0.63	0.42	1.28
Stride length (m)	0.04	0.02	0.08	0.28	0.19	0.58	0.06	0.04	0.14	0.26	0.16	0.63	0.07	0.05	0.15	0.66	0.44	1.34
Stride time (s)	0.25	0.17	0.51	0.75	0.50	1.53	0.20	0.13	0.50	0.78	0.49	1.92	0.03	0.02	0.07	0.30	0.20	0.62
Gait velocity (m/s)	0.04	0.03	0.13	0.21	0.12	0.59	0.05	0.03	0.13	0.34	0.21	0.98	0.09	0.06	0.18	0.70	0.46	1.43
Mean	-	-	-	0.58	0.38	1.21	-	-	-	0.50	0.31	1.26	-	-	-	0.52	0.34	1.07
SD	-	-	-	0.32	0.22	0.60	-	-	-	0.22	0.14	0.51	-	-	-	0.20	0.14	0.38
<u>Stair ascent</u>																		
Cadence (steps/min)	7.83	4.69	22.5	0.33	0.20	0.96	N/A	N/A	N/A	N/A	N/A	N/A	2.46	1.59	5.42	0.13	0.08	0.29
Foot off (gait cycle %)	2.33	1.50	5.13	0.77	0.50	1.70	N/A	N/A	N/A	N/A	N/A	N/A	1.43	0.92	3.14	0.48	0.31	1.05
Stride length (m)	0.04	0.03	0.09	0.50	0.32	1.11	N/A	N/A	N/A	N/A	N/A	N/A	0.04	0.02	0.08	0.70	0.45	1.55
Stride time (s)	0.36	0.23	0.79	0.79	0.51	1.75	N/A	N/A	N/A	N/A	N/A	N/A	0.03	0.02	0.07	0.14	0.09	0.31
Gait velocity (m/s)	0.05	0.03	0.11	0.34	0.22	0.74	N/A	N/A	N/A	N/A	N/A	N/A	0.09	0.06	0.18	0.70	0.46	1.43
Mean	-	-	-	0.55	0.35	1.25	-	-	-	N/A	N/A	N/A	-	-	-	0.43	0.28	0.93
SD	-	-	-	0.22	0.15	0.45	-	-	-	N/A	N/A	N/A	-	-	-	0.28	0.19	0.60
<u>Stair descent</u>																		
Cadence (steps/min)	9.83	5.12	61.8	0.30	0.16	1.88	6.39	3.83	18.35	0.31	0.18	0.88	8.26	5.46	16.8	0.54	0.35	1.09
Foot off (gait cycle %)	2.85	1.71	8.18	0.71	0.42	2.04	2.78	1.66	7.99	0.34	0.19	1.27	1.50	0.99	3.05	0.68	0.45	1.38
Stride length (m)	0.03	0.02	0.12	0.75	0.42	2.78	0.02	0.01	0.06	0.64	0.38	1.83	0.03	0.02	0.05	0.57	0.38	1.16
Stride time (s)	0.13	0.08	0.38	0.13	0.08	0.37	0.30	0.18	0.85	0.41	0.24	1.16	0.12	0.08	0.24	0.56	0.37	1.13
Gait velocity (m/s)	0.04	0.02	0.10	0.17	0.10	0.49	0.05	0.03	0.13	0.34	0.21	0.98	0.06	0.04	0.12	0.66	0.44	1.35
Mean	-	-	-	0.41	0.24	1.51	-	-	-	0.41	0.24	1.22	-	-	-	0.60	0.40	1.22
SD	-	-	-	0.30	0.17	1.05	-	-	-	0.13	0.08	0.37	-	-	-	0.06	0.04	0.13

Appendix M

Pearson's correlation coefficient *r* and the intraclass correlation of the spatiotemporal parameters at three months post-surgery in Chapter 4

Table Appendix M – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of spatiotemporal parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
Walking																		
Cadence (steps/min)	0.559	-0.241	0.906	0.603	-0.106	0.905	0.806	-0.015	0.978	0.882	0.380	0.983	0.945	0.574	0.994	0.939	0.637	0.986
Foot off (gait cycle %)	0.098	-0.652	0.751	0.107	-0.602	0.722	0.644	-0.352	0.956	0.686	-0.141	0.949	0.620	-0.151	0.922	0.679	0.023	0.926
Stride length (m)	0.922	0.621	0.986	0.948	0.764	0.989	0.939	0.535	0.993	0.973	0.824	0.996	0.580	-0.210	0.910	0.640	-0.040	0.920
Stride time (s)	0.572	-0.222	0.910	0.503	-0.246	0.876	0.453	-0.567	0.925	0.501	-0.408	0.911	0.918	0.603	0.985	0.940	0.733	0.988
Gait velocity (m/s)	0.967	0.575	0.998	0.968	0.732	0.993	0.966	0.568	0.998	0.980	0.824	0.998	0.574	-0.219	0.911	0.583	-0.136	0.900
Mean	0.624	0.016	0.910	0.626	0.108	0.897	0.762	0.034	0.970	0.804	0.296	0.967	0.727	0.119	0.944	0.756	0.243	0.944
SD	0.350	0.558	0.099	0.356	0.611	0.110	0.215	0.512	0.030	0.207	0.559	0.037	0.187	0.429	0.042	0.171	0.408	0.040
Stair ascent																		
Cadence (steps/min)	0.392	-0.750	0.947	0.920	0.410	0.984	N/A	N/A	N/A	N/A	N/A	N/A	0.999	0.991	1.000	0.991	0.951	0.999
Foot off (gait cycle %)	0.471	-0.437	0.904	0.490	-0.331	0.889	N/A	N/A	N/A	N/A	N/A	N/A	0.789	0.088	0.967	0.849	0.356	0.972
Stride length (m)	0.781	0.067	0.966	0.829	0.296	0.968	N/A	N/A	N/A	N/A	N/A	N/A	0.545	-0.353	0.920	0.602	-0.183	0.918
Stride time (s)	0.388	-0.515	0.883	0.451	-0.376	0.878	N/A	N/A	N/A	N/A	N/A	N/A	0.998	0.989	1.000	0.990	0.943	0.998
Gait velocity (m/s)	0.913	0.513	0.987	0.935	0.671	0.988	N/A	N/A	N/A	N/A	N/A	N/A	0.570	-0.220	0.910	0.580	-0.140	0.900
Mean	0.589	-0.224	0.937	0.725	0.134	0.941	N/A	N/A	N/A	N/A	N/A	N/A	0.780	0.299	0.959	0.802	0.385	0.957
SD	0.242	0.509	0.043	0.236	0.466	0.054	N/A	N/A	N/A	N/A	N/A	N/A	0.221	0.651	0.043	0.202	0.555	0.046
Stair descent																		
Cadence (steps/min)	0.959	0.498	0.997	0.949	-0.341	0.993	0.977	0.681	0.999	0.987	0.883	0.999	0.719	0.029	0.945	0.783	0.245	0.953
Foot off (gait cycle %)	0.620	-0.579	0.971	0.685	-0.284	0.962	0.901	-0.447	0.998	0.948	0.393	0.993	0.542	-0.263	0.902	0.614	-0.089	0.909
Stride length (m)	0.616	-0.846	0.991	0.561	-0.989	0.934	0.605	-0.595	0.970	0.785	-0.072	0.975	0.708	0.006	0.942	0.749	0.166	0.944
Stride time (s)	0.987	0.808	0.999	1.000	0.996	1.000	0.918	0.186	0.995	0.962	0.685	0.996	0.766	0.133	0.955	0.762	0.194	0.947
Gait velocity (m/s)	0.989	0.838	0.999	0.999	0.988	1.000	0.966	0.568	0.998	0.980	0.824	0.998	0.563	-0.235	0.908	0.638	-0.050	0.915
Mean	0.834	0.144	0.991	0.839	0.074	0.978	0.873	0.079	0.992	0.932	0.543	0.992	0.660	-0.066	0.930	0.709	0.093	0.934
SD	0.198	0.799	0.012	0.203	0.883	0.029	0.153	0.580	0.012	0.084	0.392	0.010	0.100	0.174	0.024	0.077	0.152	0.020

Appendix N

Typical error and standardised typical error of the spatiotemporal parameters at nine months post-surgery in Chapter 4

Table Appendix N – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of spatiotemporal parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Walking																		
Cadence (steps/min)	13.9	9.20	28.3	0.69	0.45	1.40	4.62	2.88	11.3	0.46	0.29	1.14	4.09	2.55	10.0	0.29	0.18	0.70
Foot off (gait cycle %)	2.59	1.67	5.70	1.01	0.65	2.22	1.12	0.72	2.47	0.68	0.44	1.50	0.85	0.56	1.74	0.63	0.42	1.28
Stride length (m)	0.03	0.02	0.07	0.25	0.16	0.55	0.08	0.05	0.17	0.39	0.25	0.86	0.07	0.05	0.15	0.66	0.44	1.34
Stride time (s)	0.31	0.20	0.68	0.92	0.60	2.04	0.06	0.04	0.13	0.50	0.32	1.09	0.03	0.02	0.07	0.30	0.20	0.62
Gait velocity (m/s)	0.04	0.02	0.14	0.18	0.10	0.67	0.02	0.01	0.05	0.31	0.19	0.77	0.09	0.06	0.18	0.70	0.46	1.43
Mean	-	-	-	0.61	0.39	1.38	-	-	-	0.47	0.30	1.07	-	-	-	0.52	0.34	1.07
SD	-	-	-	0.38	0.25	0.76	-	-	-	0.14	0.09	0.28	-	-	-	0.20	0.14	0.38
Stair ascent																		
Cadence (steps/min)	3.62	2.05	13.5	0.16	0.09	0.60	4.05	2.53	9.94	0.41	0.25	1.00	2.46	1.59	5.42	0.13	0.08	0.29
Foot off (gait cycle %)	1.82	1.17	4.01	0.47	0.30	1.03	2.05	1.28	5.04	0.67	0.42	1.64	1.43	0.92	3.14	0.48	0.31	1.05
Stride length (m)	0.03	0.02	0.06	0.36	0.23	0.79	0.04	0.03	0.10	0.81	0.51	1.99	0.04	0.02	0.08	0.70	0.45	1.55
Stride time (s)	0.11	0.07	0.24	0.26	0.17	0.57	0.10	0.06	0.24	0.45	0.28	1.10	0.03	0.02	0.07	0.14	0.09	0.31
Gait velocity (m/s)	0.05	0.03	0.12	0.29	0.19	0.63	0.02	0.01	0.04	0.29	0.18	0.71	0.09	0.06	0.18	0.70	0.46	1.43
Mean	-	-	-	0.31	0.20	0.72	-	-	-	0.53	0.33	1.29	-	-	-	0.43	0.28	0.93
SD	-	-	-	0.12	0.08	0.19	-	-	-	0.21	0.13	0.52	-	-	-	0.28	0.19	0.60
Stair descent																		
Cadence (steps/min)	1.74	0.91	10.9	0.04	0.02	0.27	3.13	1.87	8.99	0.36	0.22	1.04	8.26	5.46	16.8	0.54	0.35	1.09
Foot off (gait cycle %)	5.96	3.57	17.1	1.04	0.63	3.00	1.80	1.02	6.72	0.45	0.25	1.68	1.50	0.99	3.05	0.68	0.45	1.38
Stride length (m)	0.03	0.02	0.12	0.50	0.28	1.86	0.03	0.02	0.10	0.92	0.55	2.63	0.03	0.02	0.05	0.57	0.38	1.16
Stride time (s)	0.68	0.41	1.94	0.49	0.29	1.40	0.10	0.06	0.25	0.56	0.35	1.38	0.12	0.08	0.24	0.56	0.37	1.13
Gait velocity (m/s)	0.07	0.04	0.20	0.24	0.14	0.69	0.02	0.01	0.05	0.31	0.19	0.77	0.06	0.04	0.12	0.66	0.44	1.35
Mean	-	-	-	0.46	0.27	1.44	-	-	-	0.52	0.31	1.50	-	-	-	0.60	0.40	1.22
SD	-	-	-	0.38	0.23	1.07	-	-	-	0.24	0.15	0.72	-	-	-	0.06	0.04	0.13

Appendix O

Pearson's correlation coefficient *r* and the intraclass correlation of the spatiotemporal parameters at nine months post-surgery in Chapter 4

Table Appendix O – Pearson’s correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of spatiotemporal parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson’s *r*	95% CI		ICC	95% CI		Pearson’s *r*	95% CI		ICC	95% CI		Pearson’s *r*	95% CI		ICC	95% CI	
<u>Walking</u>																		
Cadence (steps/min)	0.404	-0.502	0.887	0.438	-0.389	0.874	0.844	0.103	0.983	0.845	0.229	0.969	0.945	0.574	0.994	0.939	0.637	0.986
Foot off (gait cycle %)	-0.025	-0.764	0.742	-0.026	-0.719	0.694	0.656	-0.191	0.943	0.629	-0.141	0.925	0.620	-0.151	0.922	0.679	0.023	0.926
Stride length (m)	0.942	0.648	0.992	0.966	0.818	0.994	0.854	0.282	0.978	0.908	0.563	0.984	0.580	-0.210	0.910	0.640	-0.040	0.920
Stride time (s)	0.243	-0.624	0.842	0.182	-0.602	0.787	0.786	0.081	0.967	0.836	0.316	0.970	0.918	0.603	0.985	0.940	0.733	0.988
Gait velocity (m/s)	0.964	0.043	0.999	0.976	0.682	0.995	0.926	0.460	0.992	0.958	0.736	0.994	0.574	-0.219	0.911	0.583	-0.136	0.900
Mean	0.506	-0.240	0.892	0.507	-0.042	0.869	0.813	0.147	0.973	0.835	0.341	0.968	0.727	0.119	0.944	0.756	0.243	0.944
SD	0.436	0.583	0.108	0.454	0.734	0.131	0.101	0.243	0.019	0.125	0.336	0.026	0.187	0.429	0.042	0.171	0.408	0.040
<u>Stair ascent</u>																		
Cadence (steps/min)	0.919	-0.358	0.998	0.981	0.744	0.996	0.894	0.302	0.988	0.919	0.535	0.988	0.999	0.991	1.000	0.991	0.951	0.999
Foot off (gait cycle %)	0.812	0.150	0.971	0.856	0.377	0.974	0.558	-0.463	0.943	0.681	-0.150	0.948	0.789	0.088	0.967	0.849	0.356	0.972
Stride length (m)	0.871	0.344	0.981	0.923	0.621	0.986	0.455	-0.565	0.925	0.440	-0.471	0.897	0.545	-0.353	0.920	0.602	-0.183	0.918
Stride time (s)	0.935	0.614	0.991	0.963	0.801	0.994	0.918	0.415	0.991	0.894	0.429	0.984	0.998	0.989	1.000	0.990	0.943	0.998
Gait velocity (m/s)	0.938	0.629	0.991	0.954	0.758	0.992	0.966	0.715	0.996	0.965	0.774	0.995	0.570	-0.220	0.910	0.580	-0.140	0.900
Mean	0.895	0.276	0.986	0.935	0.660	0.988	0.758	0.081	0.969	0.780	0.223	0.962	0.780	0.299	0.959	0.802	0.385	0.957
SD	0.054	0.407	0.011	0.049	0.172	0.009	0.234	0.565	0.032	0.219	0.516	0.041	0.221	0.651	0.043	0.202	0.555	0.046
<u>Stair descent</u>																		
Cadence (steps/min)	0.959	0.496	0.997	0.999	0.965	1.000	0.780	-0.329	0.985	0.923	0.434	0.987	0.719	0.029	0.945	0.783	0.245	0.953
Foot off (gait cycle %)	-0.092	-0.901	0.860	-0.136	-0.853	0.759	0.441	-0.903	0.985	0.856	-0.325	0.975	0.542	-0.263	0.902	0.614	-0.089	0.909
Stride length (m)	0.768	-0.737	0.995	0.860	-0.206	0.981	0.220	-0.822	0.923	0.199	-1.031	0.824	0.708	0.006	0.942	0.749	0.166	0.944
Stride time (s)	0.941	0.348	0.996	0.921	0.435	0.991	0.731	-0.198	0.968	0.804	0.127	0.970	0.766	0.133	0.955	0.762	0.194	0.947
Gait velocity (m/s)	0.955	0.461	0.997	0.995	0.955	1.000	0.926	0.460	0.992	0.958	0.736	0.994	0.563	-0.235	0.908	0.638	-0.050	0.915
Mean	0.706	-0.067	0.969	0.728	0.259	0.946	0.620	-0.358	0.971	0.748	-0.012	0.950	0.660	-0.066	0.930	0.709	0.093	0.934
SD	0.453	0.691	0.061	0.486	0.785	0.105	0.284	0.550	0.028	0.313	0.692	0.071	0.100	0.174	0.024	0.077	0.152	0.020

Appendix P

Typical error and standardised typical error of the knee kinematic parameters at pre-surgery in Chapter 4

Table Appendix P – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee kinematic parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Walking																		
Min knee flexion (°)	0.88	0.58	1.79	0.09	0.06	0.19	0.63	0.42	1.28	0.06	0.04	0.13	0.54	0.36	1.11	0.17	0.11	0.35
Max knee flexion (°)	1.44	0.95	2.93	0.13	0.09	0.27	2.76	1.82	5.61	0.29	0.19	0.59	1.23	0.81	2.50	0.43	0.28	0.87
Sagittal knee ROM (°)	0.89	0.59	1.81	0.09	0.06	0.18	3.64	2.41	7.42	0.24	0.16	0.48	1.36	0.90	2.77	0.35	0.23	0.72
Max knee abduction (°)	1.11	0.73	2.26	0.08	0.06	0.17	0.44	0.29	0.90	0.04	0.03	0.09	0.53	0.35	1.09	0.07	0.05	0.14
Max knee adduction (°)	0.73	0.44	2.09	0.06	0.03	0.16	0.81	0.53	1.64	0.07	0.05	0.14	1.11	0.74	2.27	0.19	0.13	0.38
Frontal knee ROM (°)	1.33	0.88	2.70	0.31	0.20	0.62	0.57	0.37	1.15	0.12	0.08	0.25	0.94	0.62	1.91	0.27	0.18	0.55
Max knee ext. rot. (°)	0.61	0.37	1.76	0.07	0.04	0.21	0.51	0.33	1.03	0.12	0.08	0.24	0.92	0.61	1.88	0.06	0.04	0.12
Max knee int. rot. (°)	1.01	0.67	2.06	0.14	0.09	0.28	1.01	0.67	2.05	0.18	0.12	0.36	0.85	0.56	1.72	0.05	0.04	0.11
Axial knee ROM (°)	1.00	0.66	2.04	0.33	0.22	0.66	1.28	0.85	2.61	0.36	0.24	0.73	0.95	0.63	1.94	0.27	0.18	0.54
Mean	1.00	0.65	2.16	0.14	0.09	0.30	1.29	0.85	2.63	0.16	0.11	0.33	0.94	0.62	1.91	0.21	0.14	0.42
SD	0.27	0.19	0.41	0.10	0.07	0.20	1.13	0.75	2.31	0.11	0.07	0.22	0.28	0.18	0.57	0.13	0.09	0.27
Stair ascent																		
Min knee flexion (°)	0.80	0.48	2.31	0.10	0.06	0.28	N/A	N/A	N/A	N/A	N/A	N/A	3.06	1.97	6.74	0.91	0.58	1.99
Max knee flexion (°)	2.20	1.32	6.33	0.89	0.53	2.55	N/A	N/A	N/A	N/A	N/A	N/A	1.37	0.89	3.03	0.19	0.12	0.41
Sagittal knee ROM (°)	2.30	1.38	6.60	0.32	0.19	0.93	N/A	N/A	N/A	N/A	N/A	N/A	2.23	1.43	4.90	0.29	0.19	0.63
Max knee abduction (°)	0.80	0.48	2.29	0.05	0.03	0.14	N/A	N/A	N/A	N/A	N/A	N/A	2.60	1.67	5.72	0.25	0.16	0.56
Max knee adduction (°)	1.11	0.67	3.20	0.07	0.04	0.20	N/A	N/A	N/A	N/A	N/A	N/A	4.42	2.85	9.74	0.56	0.36	1.23
Frontal knee ROM (°)	1.51	0.91	4.34	0.60	0.36	1.73	N/A	N/A	N/A	N/A	N/A	N/A	0.94	0.62	1.91	0.27	0.18	0.55
Max knee ext. rot. (°)	1.51	0.91	4.35	0.30	0.18	0.85	N/A	N/A	N/A	N/A	N/A	N/A	3.50	2.26	7.71	0.22	0.14	0.49
Max knee int. rot. (°)	2.44	1.46	7.02	0.23	0.14	0.66	N/A	N/A	N/A	N/A	N/A	N/A	2.63	1.69	5.79	0.17	0.11	0.37
Axial knee ROM (°)	2.29	1.37	6.59	0.39	0.24	1.13	N/A	N/A	N/A	N/A	N/A	N/A	4.67	3.01	10.28	0.63	0.41	1.40
Mean	1.66	1.00	4.78	0.33	0.20	0.94	N/A	N/A	N/A	N/A	N/A	N/A	2.82	1.82	6.20	0.39	0.25	0.85
SD	0.66	0.40	1.91	0.27	0.16	0.79	N/A	N/A	N/A	N/A	N/A	N/A	1.25	0.81	2.79	0.25	0.16	0.56
Stair descent																		
Min knee flexion (°)	0.65	0.39	1.86	0.12	0.07	0.36	N/A	N/A	N/A	N/A	N/A	N/A	0.81	0.53	1.64	0.23	0.15	0.46
Max knee flexion (°)	1.59	0.95	4.58	0.35	0.21	1.02	N/A	N/A	N/A	N/A	N/A	N/A	1.90	1.26	3.87	0.43	0.28	0.87
Sagittal knee ROM (°)	1.58	0.95	4.54	0.71	0.43	2.05	N/A	N/A	N/A	N/A	N/A	N/A	1.84	1.22	3.75	0.37	0.24	0.75
Max knee abduction (°)	0.62	0.37	1.79	0.04	0.03	0.12	N/A	N/A	N/A	N/A	N/A	N/A	1.15	0.76	2.35	0.12	0.08	0.23
Max knee adduction (°)	1.17	0.70	3.37	0.09	0.05	0.25	N/A	N/A	N/A	N/A	N/A	N/A	1.29	0.85	2.62	0.17	0.11	0.34
Frontal knee ROM (°)	1.46	0.87	4.19	0.35	0.21	1.01	N/A	N/A	N/A	N/A	N/A	N/A	1.27	0.84	2.59	1.27	0.84	2.59
Max knee ext. rot. (°)	1.37	0.82	3.95	0.22	0.13	0.64	N/A	N/A	N/A	N/A	N/A	N/A	1.67	1.10	3.40	0.11	0.07	0.23
Max knee int. rot. (°)	0.57	0.34	1.63	0.06	0.04	0.17	N/A	N/A	N/A	N/A	N/A	N/A	0.96	0.64	1.96	0.07	0.05	0.14
Axial knee ROM (°)	1.64	0.98	4.70	0.23	0.14	0.66	N/A	N/A	N/A	N/A	N/A	N/A	1.62	1.07	3.31	0.37	0.24	0.75
Mean	1.18	0.71	3.40	0.24	0.15	0.70	N/A	N/A	N/A	N/A	N/A	N/A	1.39	0.92	2.83	0.35	0.23	0.71
SD	0.45	0.27	1.29	0.21	0.13	0.61	N/A	N/A	N/A	N/A	N/A	N/A	0.39	0.26	0.79	0.37	0.24	0.75

Appendix Q

Pearson's correlation coefficient *r* and the intraclass correlation of the knee kinematic parameters at pre-surgery in Chapter 4

Table Appendix Q – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee kinematic parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
<u>Walking</u>																		
Min knee flexion (°)	0.993	0.961	0.999	0.995	0.975	0.999	0.999	0.994	1.000	0.997	0.988	0.999	0.971	0.844	0.995	0.982	0.913	0.996
Max knee flexion (°)	0.994	0.964	0.999	0.989	0.948	0.998	0.979	0.883	0.996	0.945	0.751	0.989	0.828	0.298	0.968	0.872	0.490	0.973
Sagittal knee ROM (°)	0.994	0.964	0.999	0.995	0.977	0.999	0.948	0.733	0.991	0.965	0.836	0.993	0.883	0.473	0.979	0.916	0.641	0.983
Max knee abduction (°)	0.994	0.963	0.999	0.996	0.979	0.999	0.998	0.989	1.000	0.999	0.994	1.000	0.995	0.973	0.999	0.997	0.985	0.999
Max knee adduction (°)	0.997	0.956	1.000	0.998	0.980	0.999	0.995	0.973	0.999	0.997	0.985	0.999	0.975	0.862	0.996	0.978	0.894	0.996
Frontal knee ROM (°)	0.926	0.639	0.987	0.939	0.728	0.987	0.985	0.917	0.997	0.991	0.955	0.998	0.927	0.640	0.987	0.953	0.784	0.990
Max knee ext. rot. (°)	0.996	0.939	1.000	0.996	0.965	0.999	0.988	0.932	0.998	0.992	0.959	0.998	0.999	0.992	1.000	0.998	0.990	1.000
Max knee int. rot. (°)	0.981	0.893	0.997	0.988	0.942	0.998	0.968	0.831	0.994	0.980	0.906	0.996	0.998	0.988	1.000	0.998	0.992	1.000
Axial knee ROM (°)	0.907	0.560	0.983	0.930	0.692	0.986	0.875	0.443	0.977	0.914	0.633	0.982	0.930	0.653	0.987	0.955	0.792	0.991
Mean	0.976	0.871	0.996	0.981	0.910	0.996	0.971	0.855	0.995	0.976	0.890	0.995	0.945	0.747	0.990	0.961	0.831	0.992
SD	0.034	0.157	0.006	0.026	0.114	0.005	0.039	0.176	0.007	0.029	0.126	0.006	0.059	0.247	0.011	0.043	0.174	0.009
<u>Stair ascent</u>																		
Min knee flexion (°)	0.998	0.963	1.000	1.000	0.999	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.216	-0.641	0.834	0.224	-0.573	0.804
Max knee flexion (°)	0.215	-0.824	0.922	0.316	-0.666	0.897	N/A	N/A	N/A	N/A	N/A	N/A	0.974	0.830	0.996	0.982	0.899	0.997
Sagittal knee ROM (°)	0.895	0.059	0.993	0.984	0.856	0.998	N/A	N/A	N/A	N/A	N/A	N/A	0.940	0.640	0.991	0.954	0.758	0.992
Max knee abduction (°)	0.999	0.978	1.000	1.000	1.000	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.938	0.627	0.991	0.965	0.813	0.994
Max knee adduction (°)	0.996	0.933	1.000	1.000	1.000	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.693	-0.126	0.950	0.780	0.164	0.958
Frontal knee ROM (°)	0.944	0.366	0.996	0.825	0.042	0.980	N/A	N/A	N/A	N/A	N/A	N/A	0.853	0.281	0.978	0.818	0.265	0.966
Max knee ext. rot. (°)	0.926	0.237	0.995	0.989	0.898	0.999	N/A	N/A	N/A	N/A	N/A	N/A	0.953	0.708	0.993	0.974	0.856	0.995
Max knee int. rot. (°)	0.966	0.569	0.998	0.996	0.962	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.972	0.818	0.996	0.986	0.919	0.997
Axial knee ROM (°)	0.852	-0.121	0.990	0.966	0.712	0.996	N/A	N/A	N/A	N/A	N/A	N/A	0.669	-0.170	0.946	0.693	-0.027	0.940
Mean	0.866	0.351	0.988	0.897	0.645	0.986	N/A	N/A	N/A	N/A	N/A	N/A	0.801	0.330	0.964	0.820	0.453	0.960
SD	0.249	0.597	0.025	0.225	0.578	0.034	N/A	N/A	N/A	N/A	N/A	N/A	0.249	0.527	0.052	0.247	0.525	0.062
<u>Stair descent</u>																		
Min knee flexion (°)	0.998	0.966	1.000	1.000	0.997	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.963	0.802	0.993	0.967	0.846	0.993
Max knee flexion (°)	0.883	0.005	0.992	0.977	0.803	0.998	N/A	N/A	N/A	N/A	N/A	N/A	0.862	0.401	0.975	0.872	0.490	0.973
Sagittal knee ROM (°)	0.517	-0.671	0.961	0.678	-0.296	0.961	N/A	N/A	N/A	N/A	N/A	N/A	0.915	0.593	0.985	0.908	0.612	0.981
Max knee abduction (°)	0.998	0.973	1.000	1.000	1.000	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.989	0.939	0.998	0.992	0.960	0.998
Max knee adduction (°)	0.994	0.902	1.000	1.000	0.999	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.98	0.900	1.000	0.980	0.920	1.000
Frontal knee ROM (°)	0.887	0.022	0.993	0.978	0.810	0.998	N/A	N/A	N/A	N/A	N/A	N/A	0.967	0.826	0.994	0.975	0.883	0.995
Max knee ext. rot. (°)	0.955	0.465	0.997	0.996	0.966	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.988	0.931	0.998	0.992	0.962	0.998
Max knee int. rot. (°)	0.997	0.952	1.000	1.000	1.000	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.997	0.980	0.999	0.997	0.986	0.999
Axial knee ROM (°)	0.966	0.570	0.998	0.996	0.961	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.866	0.415	0.975	0.908	0.610	0.981
Mean	0.911	0.465	0.993	0.958	0.804	0.995	N/A	N/A	N/A	N/A	N/A	N/A	0.947	0.754	0.991	0.955	0.808	0.991
SD	0.155	0.575	0.013	0.106	0.420	0.013	N/A	N/A	N/A	N/A	N/A	N/A	0.053	0.227	0.010	0.046	0.186	0.010

Appendix R

Typical error and standardised typical error of the knee kinematic parameters at three months post-surgery in Chapter 4

Table Appendix R – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee kinematic parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Walking																		
Min knee flexion (°)	0.80	0.53	1.63	0.16	0.10	0.32	0.65	0.42	1.43	0.12	0.08	0.26	0.54	0.36	1.11	0.17	0.11	0.35
Max knee flexion (°)	1.70	1.12	3.46	0.16	0.11	0.33	0.92	0.59	2.03	0.16	0.10	0.34	1.23	0.81	2.50	0.43	0.28	0.87
Sagittal knee ROM (°)	1.69	1.12	3.45	0.16	0.10	0.32	1.44	0.93	3.17	0.15	0.10	0.32	1.36	0.90	2.77	0.35	0.23	0.72
Max knee abduction (°)	1.85	1.22	3.77	0.20	0.14	0.42	0.92	0.60	2.03	0.15	0.10	0.33	0.53	0.35	1.09	0.07	0.05	0.14
Max knee adduction (°)	3.75	2.48	7.64	0.31	0.20	0.62	2.77	1.78	6.09	0.34	0.22	0.74	1.11	0.74	2.27	0.19	0.13	0.38
Frontal knee ROM (°)	2.41	1.59	4.89	0.37	0.25	0.76	1.96	1.26	4.31	0.63	0.41	1.39	0.94	0.62	1.91	0.27	0.18	0.55
Max knee ext. rot. (°)	2.92	1.75	8.40	0.29	0.17	0.82	2.06	1.33	4.53	0.36	0.23	0.80	0.92	0.61	1.88	0.06	0.04	0.12
Max knee int. rot. (°)	1.40	0.93	2.85	0.13	0.09	0.27	1.54	0.99	3.38	0.45	0.29	0.98	0.85	0.56	1.72	0.05	0.04	0.11
Axial knee ROM (°)	1.71	1.13	3.48	0.35	0.23	0.72	1.94	1.25	4.28	0.37	0.24	0.82	0.95	0.63	1.94	0.27	0.18	0.54
Mean	2.03	1.32	4.40	0.24	0.15	0.51	1.58	1.02	3.47	0.30	0.20	0.66	0.94	0.62	1.91	0.21	0.14	0.42
SD	0.88	0.56	2.23	0.09	0.06	0.22	0.68	0.44	1.49	0.17	0.11	0.38	0.28	0.18	0.57	0.13	0.09	0.27
Stair ascent																		
Min knee flexion (°)	1.29	0.83	2.83	0.28	0.18	0.62	N/A	N/A	N/A	N/A	N/A	N/A	3.06	1.97	6.74	0.91	0.58	1.99
Max knee flexion (°)	1.19	0.77	2.63	0.12	0.08	0.26	N/A	N/A	N/A	N/A	N/A	N/A	1.37	0.89	3.03	0.19	0.12	0.41
Sagittal knee ROM (°)	1.60	1.03	3.52	0.20	0.13	0.44	N/A	N/A	N/A	N/A	N/A	N/A	2.23	1.43	4.90	0.29	0.19	0.63
Max knee abduction (°)	1.04	0.67	2.29	0.11	0.07	0.23	N/A	N/A	N/A	N/A	N/A	N/A	2.60	1.67	5.72	0.25	0.16	0.56
Max knee adduction (°)	1.52	0.98	3.36	0.08	0.05	0.17	N/A	N/A	N/A	N/A	N/A	N/A	4.42	2.85	9.74	0.56	0.36	1.23
Frontal knee ROM (°)	1.54	0.99	3.38	0.14	0.09	0.31	N/A	N/A	N/A	N/A	N/A	N/A	0.94	0.62	1.91	0.27	0.18	0.55
Max knee ext. rot. (°)	1.17	0.75	2.57	0.10	0.07	0.23	N/A	N/A	N/A	N/A	N/A	N/A	3.50	2.26	7.71	0.22	0.14	0.49
Max knee int. rot. (°)	1.10	0.71	2.42	0.11	0.07	0.24	N/A	N/A	N/A	N/A	N/A	N/A	2.63	1.69	5.79	0.17	0.11	0.37
Axial knee ROM (°)	0.78	0.51	1.73	0.21	0.14	0.47	N/A	N/A	N/A	N/A	N/A	N/A	4.67	3.01	10.3	0.63	0.41	1.40
Mean	1.25	0.80	2.75	0.15	0.10	0.33	N/A	N/A	N/A	N/A	N/A	N/A	2.82	1.82	6.20	0.39	0.25	0.85
SD	0.27	0.17	0.59	0.07	0.04	0.15	N/A	N/A	N/A	N/A	N/A	N/A	1.25	0.81	2.79	0.25	0.16	0.56
Stair descent																		
Min knee flexion (°)	0.83	0.50	2.38	0.31	0.18	0.88	0.75	0.45	2.16	0.14	0.09	0.42	0.81	0.53	1.64	0.23	0.15	0.46
Max knee flexion (°)	2.21	1.32	6.34	0.45	0.27	1.28	2.22	1.33	6.38	0.27	0.16	0.77	1.90	1.26	3.87	0.43	0.28	0.87
Sagittal knee ROM (°)	2.14	1.28	6.16	0.49	0.29	1.41	1.55	0.93	4.46	0.12	0.07	0.34	1.84	1.22	3.75	0.37	0.24	0.75
Max knee abduction (°)	0.69	0.41	1.98	0.08	0.05	0.23	1.22	0.73	3.52	0.14	0.09	0.41	1.15	0.76	2.35	0.12	0.08	0.23
Max knee adduction (°)	2.31	1.39	6.64	0.17	0.10	0.49	2.05	1.23	5.89	0.29	0.18	0.85	1.29	0.85	2.62	0.17	0.11	0.34
Frontal knee ROM (°)	2.53	1.52	7.27	0.32	0.19	0.93	2.41	1.44	6.92	0.86	0.52	2.47	1.27	0.84	2.59	1.27	0.84	2.59
Max knee ext. rot. (°)	0.58	0.35	1.68	0.08	0.05	0.23	1.93	1.16	5.55	0.37	0.22	1.07	1.67	1.10	3.40	0.11	0.07	0.23
Max knee int. rot. (°)	1.21	0.73	3.48	0.12	0.07	0.35	0.91	0.54	2.61	0.17	0.10	0.50	0.96	0.64	1.96	0.07	0.05	0.14
Axial knee ROM (°)	1.07	0.64	3.09	0.21	0.12	0.59	2.41	1.45	6.93	1.23	0.74	3.54	1.62	1.07	3.31	0.37	0.24	0.75
Mean	1.51	0.90	4.34	0.25	0.15	0.71	1.72	1.03	4.94	0.40	0.24	1.15	1.39	0.92	2.83	0.35	0.23	0.71
SD	0.78	0.47	2.24	0.15	0.09	0.44	0.64	0.38	1.82	0.39	0.23	1.11	0.39	0.26	0.79	0.37	0.24	0.75

Appendix S

Pearson's correlation coefficient *r* and the intraclass correlation of the knee kinematic parameters at three months post-surgery in Chapter 4

Table Appendix S – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee kinematic parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
<u>Walking</u>																		
Min knee flexion (°)	0.976	0.871	0.996	0.985	0.927	0.997	0.991	0.937	0.999	0.993	0.960	0.999	0.971	0.844	0.995	0.982	0.913	0.996
Max knee flexion (°)	0.982	0.903	0.997	0.984	0.923	0.997	0.985	0.899	0.998	0.987	0.928	0.998	0.828	0.298	0.968	0.872	0.490	0.973
Sagittal knee ROM (°)	0.977	0.873	0.996	0.985	0.927	0.997	0.979	0.862	0.997	0.989	0.936	0.998	0.883	0.473	0.979	0.916	0.641	0.983
Max knee abduction (°)	0.959	0.784	0.993	0.974	0.876	0.995	0.977	0.848	0.997	0.988	0.933	0.998	0.995	0.973	0.999	0.997	0.985	0.999
Max knee adduction (°)	0.916	0.596	0.985	0.938	0.726	0.987	0.896	0.441	0.985	0.934	0.670	0.988	0.975	0.862	0.996	0.978	0.894	0.996
Frontal knee ROM (°)	0.877	0.452	0.978	0.905	0.602	0.980	0.634	-0.228	0.939	0.699	-0.016	0.941	0.927	0.640	0.987	0.953	0.784	0.990
Max knee ext. rot. (°)	0.947	0.390	0.997	0.936	0.504	0.985	0.886	0.400	0.983	0.922	0.618	0.986	0.999	0.992	1.000	0.998	0.990	1.000
Max knee int. rot. (°)	0.983	0.904	0.997	0.989	0.948	0.998	0.815	0.160	0.972	0.872	0.431	0.977	0.998	0.988	1.000	0.998	0.992	1.000
Axial knee ROM (°)	0.926	0.636	0.987	0.916	0.642	0.983	0.908	0.491	0.987	0.918	0.601	0.985	0.930	0.653	0.987	0.955	0.792	0.991
Mean	0.949	0.712	0.992	0.957	0.786	0.991	0.897	0.534	0.984	0.922	0.673	0.986	0.945	0.747	0.990	0.961	0.831	0.992
SD	0.037	0.200	0.007	0.033	0.170	0.007	0.115	0.395	0.019	0.094	0.321	0.018	0.059	0.247	0.011	0.043	0.174	0.009
<u>Stair ascent</u>																		
Min knee flexion (°)	0.929	0.583	0.990	0.955	0.766	0.992	N/A	N/A	N/A	N/A	N/A	N/A	0.216	-0.641	0.834	0.224	-0.573	0.804
Max knee flexion (°)	0.997	0.976	1.000	0.993	0.960	0.999	N/A	N/A	N/A	N/A	N/A	N/A	0.974	0.830	0.996	0.982	0.899	0.997
Sagittal knee ROM (°)	0.960	0.749	0.994	0.979	0.884	0.996	N/A	N/A	N/A	N/A	N/A	N/A	0.940	0.640	0.991	0.954	0.758	0.992
Max knee abduction (°)	0.992	0.943	0.999	0.994	0.968	0.999	N/A	N/A	N/A	N/A	N/A	N/A	0.938	0.627	0.991	0.965	0.813	0.994
Max knee adduction (°)	1.000	0.970	1.000	1.000	0.980	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.693	-0.126	0.950	0.780	0.164	0.958
Frontal knee ROM (°)	0.984	0.891	0.998	0.990	0.943	0.998	N/A	N/A	N/A	N/A	N/A	N/A	0.853	0.281	0.978	0.818	0.265	0.966
Max knee ext. rot. (°)	0.989	0.927	0.998	0.994	0.968	0.999	N/A	N/A	N/A	N/A	N/A	N/A	0.953	0.708	0.993	0.974	0.856	0.995
Max knee int. rot. (°)	0.989	0.922	0.998	0.994	0.966	0.999	N/A	N/A	N/A	N/A	N/A	N/A	0.972	0.818	0.996	0.986	0.919	0.997
Axial knee ROM (°)	0.962	0.761	0.995	0.976	0.867	0.996	N/A	N/A	N/A	N/A	N/A	N/A	0.669	-0.170	0.946	0.693	-0.027	0.940
Mean	0.978	0.858	0.997	0.986	0.922	0.998	N/A	N/A	N/A	N/A	N/A	N/A	0.801	0.330	0.964	0.820	0.453	0.960
SD	0.023	0.133	0.003	0.014	0.071	0.003	N/A	N/A	N/A	N/A	N/A	N/A	0.249	0.527	0.052	0.247	0.525	0.062
<u>Stair descent</u>																		
Min knee flexion (°)	0.955	0.460	0.997	0.987	0.883	0.999	0.979	0.710	0.999	0.999	0.994	1.000	0.963	0.802	0.993	0.967	0.846	0.993
Max knee flexion (°)	0.866	-0.069	0.991	0.944	0.567	0.994	0.940	0.335	0.996	0.992	0.929	0.999	0.862	0.401	0.975	0.872	0.490	0.973
Sagittal knee ROM (°)	0.809	-0.255	0.987	0.920	0.429	0.991	0.990	0.855	0.999	1.000	0.997	1.000	0.915	0.593	0.985	0.908	0.612	0.981
Max knee abduction (°)	0.998	0.973	1.000	1.000	0.999	1.000	0.982	0.749	0.999	0.999	0.994	1.000	0.989	0.939	0.998	0.992	0.960	0.998
Max knee adduction (°)	0.971	0.622	0.998	0.999	0.988	1.000	0.974	0.656	0.998	0.989	0.899	0.999	0.980	0.900	1.000	0.980	0.920	1.000
Frontal knee ROM (°)	0.899	0.083	0.993	0.984	0.856	0.998	0.261	-0.807	0.929	0.382	-0.622	0.911	0.967	0.826	0.994	0.975	0.883	0.995
Max knee ext. rot. (°)	0.993	0.900	1.000	1.000	0.999	1.000	0.863	-0.079	0.991	0.973	0.765	0.997	0.988	0.931	0.998	0.992	0.962	0.998
Max knee int. rot. (°)	0.986	0.796	0.999	1.000	0.997	1.000	0.977	0.691	0.999	0.999	0.987	1.000	0.997	0.980	0.999	0.997	0.986	0.999
Axial knee ROM (°)	0.958	0.488	0.997	0.997	0.975	1.000	-0.578	-0.967	0.621	-0.707	-0.965	0.244	0.866	0.415	0.975	0.908	0.610	0.981
Mean	0.937	0.444	0.996	0.981	0.855	0.998	0.710	0.238	0.948	0.736	0.553	0.906	0.947	0.754	0.991	0.955	0.808	0.991
SD	0.065	0.437	0.004	0.029	0.212	0.003	0.536	0.698	0.125	0.578	0.772	0.250	0.053	0.227	0.010	0.046	0.186	0.010

Appendix T

Typical error and standardised typical error of the knee kinematic parameters at nine months post-surgery in Chapter 4

Table Appendix T – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee kinematic parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Walking																		
Min knee flexion (°)	0.99	0.64	2.18	0.19	0.12	0.41	0.58	0.37	1.28	0.13	0.08	0.29	0.54	0.36	1.11	0.17	0.11	0.35
Max knee flexion (°)	0.63	0.41	1.39	0.16	0.10	0.34	1.25	0.80	2.75	0.16	0.10	0.35	1.23	0.81	2.50	0.43	0.28	0.87
Sagittal knee ROM (°)	1.22	0.79	2.69	0.18	0.12	0.40	1.38	0.89	3.05	0.15	0.09	0.32	1.36	0.90	2.77	0.35	0.23	0.72
Max knee abduction (°)	0.46	0.30	1.01	0.04	0.02	0.08	0.59	0.38	1.29	0.09	0.06	0.20	0.53	0.35	1.09	0.07	0.05	0.14
Max knee adduction (°)	0.80	0.52	1.76	0.68	0.44	1.50	0.68	0.44	1.50	0.14	0.09	0.30	1.11	0.74	2.27	0.19	0.13	0.38
Frontal knee ROM (°)	1.17	0.76	2.58	0.17	0.11	0.36	0.87	0.56	1.91	0.38	0.24	0.83	0.94	0.62	1.91	0.27	0.18	0.55
Max knee ext. rot. (°)	1.29	0.73	4.83	0.09	0.05	0.35	0.71	0.45	1.55	0.14	0.09	0.30	0.92	0.61	1.88	0.06	0.04	0.12
Max knee int. rot. (°)	1.43	0.92	3.15	0.09	0.06	0.20	1.19	0.76	2.61	0.16	0.10	0.36	0.85	0.56	1.72	0.05	0.04	0.11
Axial knee ROM (°)	1.43	0.92	3.15	0.31	0.20	0.68	1.50	0.97	3.31	0.29	0.19	0.65	0.95	0.63	1.94	0.27	0.18	0.54
Mean	1.05	0.67	2.53	0.21	0.14	0.48	0.97	0.62	2.14	0.18	0.12	0.40	0.94	0.62	1.91	0.21	0.14	0.42
SD	0.35	0.22	1.14	0.19	0.13	0.42	0.36	0.23	0.80	0.09	0.06	0.20	0.28	0.18	0.57	0.13	0.09	0.27
Stair ascent																		
Min knee flexion (°)	1.11	0.71	2.44	0.19	0.12	0.42	0.77	0.48	1.89	0.35	0.22	0.85	3.06	1.97	6.74	0.91	0.58	1.99
Max knee flexion (°)	1.12	0.72	2.46	0.13	0.08	0.28	1.66	1.04	4.07	0.29	0.18	0.70	1.37	0.89	3.03	0.19	0.12	0.41
Sagittal knee ROM (°)	1.12	0.72	2.46	0.11	0.07	0.24	2.19	1.37	5.37	0.36	0.22	0.88	2.23	1.43	4.90	0.29	0.19	0.63
Max knee abduction (°)	0.49	0.32	1.08	0.03	0.02	0.07	1.05	0.66	2.58	0.10	0.06	0.25	2.60	1.67	5.72	0.25	0.16	0.56
Max knee adduction (°)	0.59	0.38	1.31	0.03	0.02	0.07	1.32	0.82	3.24	0.20	0.13	0.50	4.42	2.85	9.74	0.56	0.36	1.23
Frontal knee ROM (°)	0.88	0.57	1.94	0.11	0.07	0.24	1.93	1.21	4.74	0.25	0.16	0.61	0.94	0.62	1.91	0.27	0.18	0.55
Max knee ext. rot. (°)	1.24	0.80	2.72	0.09	0.06	0.20	0.87	0.54	2.13	0.14	0.09	0.35	3.50	2.26	7.71	0.22	0.14	0.49
Max knee int. rot. (°)	1.87	1.21	4.13	0.14	0.09	0.31	1.55	0.97	3.81	0.20	0.13	0.50	2.63	1.69	5.79	0.17	0.11	0.37
Axial knee ROM (°)	2.12	1.36	4.66	0.35	0.22	0.77	2.30	1.44	5.65	0.65	0.41	1.59	4.67	3.01	10.3	0.63	0.41	1.40
Mean	1.17	0.75	2.58	0.13	0.08	0.29	1.52	0.95	3.72	0.28	0.18	0.69	2.82	1.82	6.20	0.39	0.25	0.85
SD	0.53	0.34	1.18	0.10	0.06	0.21	0.56	0.35	1.37	0.16	0.10	0.40	1.25	0.81	2.79	0.25	0.16	0.56
Stair descent																		
Min knee flexion (°)	0.82	0.49	2.37	0.27	0.16	0.78	0.79	0.49	1.93	0.22	0.14	0.53	0.81	0.53	1.64	0.23	0.15	0.46
Max knee flexion (°)	0.76	0.46	2.19	0.10	0.06	0.28	0.96	0.60	2.36	0.12	0.07	0.29	1.90	1.26	3.87	0.43	0.28	0.87
Sagittal knee ROM (°)	0.61	0.35	2.28	0.06	0.04	0.24	1.60	1.00	3.93	0.19	0.12	0.47	1.84	1.22	3.75	0.37	0.24	0.75
Max knee abduction (°)	0.81	0.49	2.33	0.06	0.04	0.18	3.10	1.93	7.60	0.30	0.19	0.74	1.15	0.76	2.35	0.12	0.08	0.23
Max knee adduction (°)	0.43	0.26	1.23	0.03	0.02	0.08	1.16	0.72	2.84	0.15	0.09	0.36	1.29	0.85	2.62	0.17	0.11	0.34
Frontal knee ROM (°)	0.72	0.43	2.06	0.13	0.08	0.38	2.50	1.56	6.13	0.35	0.22	0.86	1.27	0.84	2.59	1.27	0.84	2.59
Max knee ext. rot. (°)	0.57	0.34	1.64	0.08	0.05	0.23	2.33	1.46	5.72	0.31	0.19	0.75	1.67	1.10	3.40	0.11	0.07	0.23
Max knee int. rot. (°)	3.97	2.38	11.4	0.60	0.36	1.73	2.49	1.55	6.10	0.27	0.17	0.67	0.96	0.64	1.96	0.07	0.05	0.14
Axial knee ROM (°)	4.17	2.50	12.0	1.10	0.66	3.16	1.54	0.96	3.78	0.49	0.31	1.21	1.62	1.07	3.31	0.37	0.24	0.75
Mean	1.43	0.86	4.17	0.27	0.16	0.78	1.83	1.14	4.49	0.27	0.17	0.65	1.39	0.92	2.83	0.35	0.23	0.71
SD	1.50	0.90	4.29	0.36	0.21	1.03	0.80	0.50	1.97	0.11	0.07	0.28	0.39	0.26	0.79	0.37	0.24	0.75

Appendix U

Pearson's correlation coefficient *r* and the intraclass correlation of the knee kinematic parameters at nine months post-surgery in Chapter 4

Table Appendix U – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee kinematic parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
<u>Walking</u>																		
Min knee flexion (°)	0.967	0.786	0.995	0.982	0.898	0.997	0.984	0.891	0.998	0.991	0.951	0.999	0.971	0.844	0.995	0.982	0.913	0.996
Max knee flexion (°)	0.980	0.864	0.997	0.987	0.928	0.998	0.976	0.842	0.997	0.987	0.925	0.998	0.828	0.298	0.968	0.872	0.490	0.973
Sagittal knee ROM (°)	0.967	0.785	0.995	0.982	0.902	0.997	0.992	0.944	0.999	0.989	0.937	0.998	0.883	0.473	0.979	0.916	0.641	0.983
Max knee abduction (°)	0.999	0.994	1.000	0.999	0.996	1.000	0.992	0.945	0.999	0.996	0.977	0.999	0.995	0.973	0.999	0.997	0.985	0.999
Max knee adduction (°)	0.996	0.973	0.999	0.998	0.987	1.000	0.984	0.893	0.998	0.990	0.944	0.998	0.975	0.862	0.996	0.978	0.894	0.996
Frontal knee ROM (°)	0.981	0.875	0.997	0.986	0.920	0.998	0.859	0.300	0.979	0.915	0.590	0.985	0.927	0.640	0.987	0.953	0.784	0.990
Max knee ext. rot. (°)	0.988	0.543	1.000	0.994	0.909	0.999	0.982	0.876	0.997	0.990	0.946	0.998	0.999	0.992	1.000	0.998	0.990	1.000
Max knee int. rot. (°)	0.993	0.951	0.999	0.996	0.977	0.999	0.975	0.833	0.996	0.986	0.924	0.998	0.998	0.988	1.000	0.998	0.992	1.000
Axial knee ROM (°)	0.907	0.485	0.986	0.945	0.717	0.990	0.914	0.518	0.987	0.952	0.748	0.992	0.930	0.653	0.987	0.955	0.792	0.991
Mean	0.975	0.806	0.996	0.985	0.915	0.998	0.962	0.782	0.994	0.977	0.882	0.996	0.945	0.747	0.990	0.961	0.831	0.992
SD	0.028	0.182	0.004	0.017	0.083	0.003	0.045	0.222	0.007	0.027	0.128	0.005	0.059	0.247	0.011	0.043	0.174	0.009
<u>Stair ascent</u>																		
Min knee flexion (°)	0.967	0.786	0.995	0.981	0.895	0.997	0.882	0.248	0.987	0.947	0.673	0.992	0.216	-0.641	0.834	0.224	-0.573	0.804
Max knee flexion (°)	0.992	0.943	0.999	0.992	0.952	0.999	0.959	0.667	0.996	0.966	0.781	0.995	0.974	0.830	0.996	0.982	0.899	0.997
Sagittal knee ROM (°)	0.988	0.918	0.998	0.994	0.965	0.999	0.970	0.745	0.997	0.942	0.648	0.992	0.940	0.640	0.991	0.954	0.758	0.992
Max knee abduction (°)	0.999	0.992	1.000	0.999	0.997	1.000	0.994	0.943	0.999	0.996	0.974	0.999	0.938	0.627	0.991	0.965	0.813	0.994
Max knee adduction (°)	0.999	0.994	1.000	1.000	0.997	1.000	0.971	0.749	0.997	0.985	0.896	0.998	0.693	-0.126	0.950	0.780	0.164	0.958
Frontal knee ROM (°)	0.988	0.920	0.998	0.994	0.965	0.999	0.944	0.567	0.994	0.976	0.838	0.997	0.853	0.281	0.978	0.818	0.265	0.966
Max knee ext. rot. (°)	0.992	0.943	0.999	0.996	0.975	0.999	0.989	0.897	0.999	0.993	0.949	0.999	0.953	0.708	0.993	0.974	0.856	0.995
Max knee int. rot. (°)	0.981	0.870	0.997	0.990	0.943	0.998	0.969	0.741	0.997	0.985	0.895	0.998	0.972	0.818	0.996	0.986	0.919	0.997
Axial knee ROM (°)	0.880	0.377	0.982	0.929	0.647	0.987	0.598	-0.415	0.949	0.707	-0.101	0.953	0.669	-0.170	0.946	0.693	-0.027	0.940
Mean	0.976	0.860	0.996	0.986	0.926	0.998	0.920	0.571	0.991	0.944	0.728	0.991	0.801	0.330	0.964	0.820	0.453	0.960
SD	0.037	0.192	0.006	0.022	0.109	0.004	0.125	0.421	0.016	0.091	0.331	0.015	0.249	0.527	0.052	0.247	0.525	0.062
<u>Stair descent</u>																		
Min knee flexion (°)	0.932	0.278	0.996	0.992	0.926	0.999	0.953	0.622	0.995	0.982	0.878	0.997	0.963	0.802	0.993	0.967	0.846	0.993
Max knee flexion (°)	0.991	0.862	0.999	1.000	0.999	1.000	0.993	0.933	0.999	0.995	0.966	0.999	0.862	0.401	0.975	0.872	0.490	0.973
Sagittal knee ROM (°)	0.996	0.802	1.000	0.999	0.979	1.000	0.975	0.785	0.997	0.986	0.907	0.998	0.915	0.593	0.985	0.908	0.612	0.981
Max knee abduction (°)	0.998	0.971	1.000	1.000	1.000	1.000	0.974	0.778	0.997	0.962	0.757	0.995	0.989	0.939	0.998	0.992	0.960	0.998
Max knee adduction (°)	0.999	0.991	1.000	1.000	1.000	1.000	0.982	0.843	0.998	0.992	0.947	0.999	0.980	0.900	1.000	0.980	0.920	1.000
Frontal knee ROM (°)	0.983	0.763	0.999	1.000	0.995	1.000	0.920	0.430	0.991	0.945	0.665	0.992	0.967	0.826	0.994	0.975	0.883	0.995
Max knee ext. rot. (°)	0.995	0.925	1.000	1.000	0.999	1.000	0.933	0.501	0.993	0.961	0.749	0.994	0.988	0.931	0.998	0.992	0.962	0.998
Max knee int. rot. (°)	0.640	-0.557	0.973	0.829	0.052	0.981	0.932	0.495	0.993	0.970	0.802	0.996	0.997	0.980	0.999	0.997	0.986	0.999
Axial knee ROM (°)	-0.309	-0.936	0.788	-0.305	-0.895	0.673	0.770	-0.10	0.97	0.86	0.31	0.98	0.866	0.415	0.975	0.908	0.610	0.981
Mean	0.803	0.455	0.973	0.835	0.673	0.961	0.937	0.587	0.993	0.961	0.776	0.994	0.947	0.754	0.991	0.955	0.808	0.991
SD	0.433	0.720	0.070	0.431	0.664	0.108	0.067	0.311	0.009	0.041	0.201	0.006	0.053	0.227	0.010	0.046	0.186	0.010

Appendix V

Typical error and standardised typical error of the knee kinetic parameters at pre-surgery in Chapter 4

Table Appendix V – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee kinetic parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Walking																		
Max knee ext. mom (Nm/kg)	0.26	0.17	0.53	0.19	0.13	0.39	0.24	0.16	0.49	0.34	0.22	0.69	0.32	0.21	0.66	0.62	0.41	1.26
Max knee flx. mom (Nm/kg)	0.52	0.35	1.07	0.15	0.10	0.31	0.65	0.43	1.32	0.23	0.15	0.47	0.71	0.47	1.44	0.23	0.16	0.48
Knee flx at max ext. mom (°)	1.72	1.14	3.51	0.18	0.12	0.36	7.08	4.68	14.4	0.59	0.39	1.20	1.81	1.20	3.69	0.44	0.29	0.90
Knee flx at max flx. mom (°)	2.62	1.73	5.33	0.22	0.15	0.45	2.15	1.42	4.37	0.28	0.19	0.58	0.92	0.61	1.88	0.16	0.11	0.34
Max knee ab. mom (Nm/kg)	0.15	0.10	0.31	0.09	0.06	0.18	0.14	0.09	0.29	0.31	0.20	0.62	0.18	0.12	0.36	0.43	0.29	0.88
Max knee add. mom (Nm/kg)	0.31	0.21	0.64	0.20	0.13	0.40	0.47	0.31	0.95	0.18	0.12	0.37	0.36	0.24	0.73	0.28	0.18	0.57
Max knee ext. mom (Nm/kg)	0.04	0.03	0.08	0.77	0.51	1.56	0.17	0.11	0.35	0.22	0.15	0.46	0.09	0.06	0.17	0.74	0.49	1.50
Max knee int. mom (Nm/kg)	0.11	0.08	0.23	0.13	0.09	0.27	0.30	0.20	0.62	0.07	0.05	0.14	0.14	0.09	0.28	0.36	0.24	0.74
Mean	-	-	-	0.24	0.16	0.49	-	-	-	0.28	0.18	0.57	-	-	-	0.41	0.27	0.83
SD	-	-	-	0.22	0.14	0.44	-	-	-	0.15	0.10	0.31	-	-	-	0.20	0.13	0.39
Stair ascent																		
Max knee ext. mom (Nm/kg)	0.44	0.26	1.26	0.11	0.06	0.30	N/A	N/A	N/A	N/A	N/A	N/A	0.48	0.31	1.06	0.33	0.21	0.72
Max knee flx. mom (Nm/kg)	0.40	0.24	1.16	0.09	0.05	0.25	N/A	N/A	N/A	N/A	N/A	N/A	0.47	0.30	1.02	0.13	0.08	0.29
Knee flx at max ext. mom (°)	27.0	16.2	77.6	0.80	0.48	2.31	N/A	N/A	N/A	N/A	N/A	N/A	3.30	2.13	7.28	0.12	0.08	0.26
Knee flx at max flx. mom (°)	3.94	2.36	11.3	0.20	0.12	0.58	N/A	N/A	N/A	N/A	N/A	N/A	5.82	3.75	12.8	0.80	0.52	1.77
Max knee ab. mom (Nm/kg)	0.23	0.14	0.66	0.36	0.22	1.04	N/A	N/A	N/A	N/A	N/A	N/A	0.23	0.15	0.51	0.29	0.18	0.63
Max knee add. mom (Nm/kg)	0.61	0.36	1.75	0.30	0.18	0.87	N/A	N/A	N/A	N/A	N/A	N/A	0.37	0.24	0.82	0.25	0.16	0.55
Max knee ext. mom (Nm/kg)	0.02	0.01	0.06	0.14	0.08	0.41	N/A	N/A	N/A	N/A	N/A	N/A	0.08	0.05	0.17	0.19	0.12	0.42
Max knee int. mom (Nm/kg)	0.07	0.04	0.19	0.04	0.03	0.13	N/A	N/A	N/A	N/A	N/A	N/A	0.22	0.14	0.48	0.30	0.19	0.66
Mean	-	-	-	0.26	0.15	0.74	-	-	-	N/A	N/A	N/A	-	-	-	0.30	0.19	0.66
SD	-	-	-	0.25	0.15	0.71	-	-	-	N/A	N/A	N/A	-	-	-	0.22	0.14	0.48
Stair descent																		
Max knee ext. mom (Nm/kg)	0.36	0.22	1.05	0.36	0.21	1.03	N/A	N/A	N/A	N/A	N/A	N/A	0.44	0.29	0.90	0.53	0.35	1.08
Max knee flx. mom (Nm/kg)	1.36	0.81	3.91	0.20	0.12	0.57	N/A	N/A	N/A	N/A	N/A	N/A	0.57	0.38	1.15	0.29	0.19	0.60
Knee flx at max ext. mom (°)	24.6	14.7	70.7	1.04	0.63	3.00	N/A	N/A	N/A	N/A	N/A	N/A	3.89	2.57	7.91	0.53	0.35	1.08
Knee flx at max flx. mom (°)	16.3	9.79	47.0	0.79	0.47	2.27	N/A	N/A	N/A	N/A	N/A	N/A	12.7	8.41	25.9	0.78	0.51	1.58
Max knee ab. mom (Nm/kg)	39.4	23.6	113	0.53	0.32	1.53	N/A	N/A	N/A	N/A	N/A	N/A	0.20	0.13	0.40	0.57	0.37	1.15
Max knee add. mom (Nm/kg)	8.18	4.90	23.5	0.17	0.10	0.48	N/A	N/A	N/A	N/A	N/A	N/A	0.33	0.22	0.68	0.20	0.13	0.41
Max knee ext. mom (Nm/kg)	1.62	0.97	4.67	0.06	0.03	0.16	N/A	N/A	N/A	N/A	N/A	N/A	0.11	0.08	0.23	0.26	0.17	0.52
Max knee int. mom (Nm/kg)	1.31	0.79	3.77	0.08	0.05	0.23	N/A	N/A	N/A	N/A	N/A	N/A	0.19	0.12	0.38	0.33	0.22	0.67
Mean	-	-	-	0.40	0.24	1.16	-	-	-	N/A	N/A	N/A	-	-	-	0.44	0.29	0.89
SD	-	-	-	0.36	0.22	1.03	-	-	-	N/A	N/A	N/A	-	-	-	0.20	0.13	0.40

Appendix W

Pearson's correlation coefficient *r* and the intraclass correlation of the knee kinetic parameters at pre-surgery in Chapter 4

Table Appendix W – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee kinetic parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
<u>Walking</u>																		
Max knee ext. mom (Nm/kg)	0.968	0.830	0.994	0.977	0.891	0.995	0.886	0.484	0.979	0.924	0.671	0.984	0.629	-0.136	0.924	0.692	0.047	0.930
Max knee flx. mom (Nm/kg)	0.982	0.898	0.997	0.985	0.929	0.997	0.957	0.775	0.992	0.966	0.843	0.993	0.953	0.755	0.992	0.965	0.837	0.993
Knee flx at max ext. mom (°)	0.970	0.838	0.995	0.980	0.905	0.996	0.721	0.033	0.945	0.726	0.116	0.939	0.811	0.248	0.964	0.861	0.457	0.971
Knee flx at max flx. mom (°)	0.956	0.770	0.992	0.969	0.853	0.994	0.922	0.620	0.986	0.948	0.765	0.989	0.973	0.853	0.995	0.983	0.919	0.997
Max knee ab. mom (Nm/kg)	0.997	0.985	1.000	0.996	0.978	0.999	0.976	0.869	0.996	0.939	0.729	0.988	0.814	0.256	0.965	0.869	0.480	0.972
Max knee add. mom (Nm/kg)	0.962	0.799	0.993	0.976	0.884	0.995	0.968	0.827	0.994	0.979	0.902	0.996	0.926	0.637	0.987	0.950	0.771	0.990
Max knee ext. mom (Nm/kg)	0.410	-0.415	0.865	0.478	-0.277	0.868	0.989	0.937	0.998	0.968	0.850	0.994	0.457	-0.366	0.879	0.527	-0.214	0.883
Max knee int. mom (Nm/kg)	0.984	0.910	0.997	0.989	0.948	0.998	0.995	0.973	0.999	0.997	0.986	0.999	0.869	0.423	0.976	0.911	0.624	0.982
Mean	0.904	0.702	0.979	0.919	0.764	0.980	0.927	0.690	0.986	0.931	0.733	0.985	0.804	0.334	0.960	0.845	0.490	0.965
SD	0.200	0.456	0.046	0.178	0.422	0.045	0.091	0.311	0.018	0.086	0.268	0.019	0.178	0.426	0.040	0.158	0.395	0.039
<u>Stair ascent</u>																		
Max knee ext. mom (Nm/kg)	0.997	0.951	1.000	1.000	0.998	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.937	0.626	0.991	0.938	0.685	0.989
Max knee flx. mom (Nm/kg)	0.994	0.907	1.000	1.000	0.999	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.984	0.890	0.998	0.991	0.951	0.999
Knee flx at max ext. mom (°)	0.361	-0.765	0.943	0.508	-0.516	0.934	N/A	N/A	N/A	N/A	N/A	N/A	0.990	0.928	0.999	0.993	0.960	0.999
Knee flx at max flx. mom (°)	0.978	0.702	0.999	0.998	0.977	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.353	-0.545	0.874	0.430	-0.398	0.872
Max knee ab. mom (Nm/kg)	0.965	0.558	0.998	0.976	0.788	0.997	N/A	N/A	N/A	N/A	N/A	N/A	0.920	0.544	0.988	0.954	0.758	0.992
Max knee add. mom (Nm/kg)	0.969	0.595	0.998	0.988	0.887	0.999	N/A	N/A	N/A	N/A	N/A	N/A	0.941	0.645	0.991	0.965	0.814	0.994
Max knee ext. mom (Nm/kg)	0.996	0.937	1.000	0.999	0.994	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.964	0.768	0.995	0.981	0.893	0.997
Max knee int. mom (Nm/kg)	0.998	0.975	1.000	1.000	1.000	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.923	0.555	0.989	0.949	0.735	0.991
Mean	0.907	0.608	0.992	0.934	0.766	0.991	N/A	N/A	N/A	N/A	N/A	N/A	0.877	0.551	0.978	0.900	0.675	0.979
SD	0.221	0.579	0.020	0.172	0.523	0.023	N/A	N/A	N/A	N/A	N/A	N/A	0.213	0.466	0.042	0.191	0.445	0.043
<u>Stair descent</u>																		
Max knee ext. mom (Nm/kg)	0.906	0.120	0.994	0.977	0.797	0.998	N/A	N/A	N/A	N/A	N/A	N/A	0.810	0.245	0.964	0.789	0.259	0.954
Max knee flx. mom (Nm/kg)	0.966	0.562	0.998	0.998	0.979	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.914	0.587	0.984	0.944	0.748	0.989
Knee flx at max ext. mom (°)	-0.212	-0.922	0.825	-0.136	-0.853	0.759	N/A	N/A	N/A	N/A	N/A	N/A	0.933	0.668	0.988	0.786	0.251	0.953
Knee flx at max flx. mom (°)	0.412	-0.739	0.949	0.539	-0.484	0.939	N/A	N/A	N/A	N/A	N/A	N/A	0.445	-0.378	0.875	0.465	-0.292	0.864
Max knee ab. mom (Nm/kg)	1.000	1.000	1.000	0.891	0.286	0.988	N/A	N/A	N/A	N/A	N/A	N/A	0.731	0.054	0.948	0.752	0.171	0.945
Max knee add. mom (Nm/kg)	1.000	0.996	1.000	0.999	0.989	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.959	0.783	0.993	0.974	0.877	0.995
Max knee ext. mom (Nm/kg)	1.000	1.000	1.000	1.000	1.000	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.936	0.682	0.989	0.958	0.808	0.992
Max knee int. mom (Nm/kg)	1.000	1.000	1.000	1.000	0.999	1.000	N/A	N/A	N/A	N/A	N/A	N/A	0.938	0.688	0.989	0.928	0.686	0.985
Mean	0.759	0.377	0.971	0.784	0.464	0.961	N/A	N/A	N/A	N/A	N/A	N/A	0.833	0.416	0.966	0.825	0.439	0.960
SD	0.441	0.809	0.061	0.404	0.745	0.084	N/A	N/A	N/A	N/A	N/A	N/A	0.175	0.408	0.040	0.170	0.407	0.043

Appendix X

Typical error and standardised typical error of the knee kinetic parameters at three months post-surgery in Chapter 4

Table Appendix X – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee kinetic parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. $STE<0.2$ = trivial; $0.2 \leq STE<0.6$ = small; $0.6 \leq STE<1.2$ = moderate; $1.2 \leq STE<2$ = large; $STE \geq 2$ = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
<u>Walking</u>																		
Max knee ext. mom (Nm/kg)	0.16	0.11	0.32	0.10	0.07	0.21	0.03	-0.07	0.14	0.07	0.04	0.17	0.32	0.21	0.66	0.62	0.41	1.26
Max knee flx. mom (Nm/kg)	0.31	0.21	0.64	0.09	0.06	0.19	0.18	0.11	0.45	0.05	0.03	0.11	0.71	0.47	1.44	0.23	0.16	0.48
Knee flx at max ext. mom (°)	1.24	0.82	2.52	0.20	0.13	0.41	1.40	0.88	3.44	0.26	0.16	0.63	1.81	1.20	3.69	0.44	0.29	0.90
Knee flx at max flx. mom (°)	1.40	0.92	2.85	0.26	0.17	0.53	0.93	0.58	2.28	0.18	0.11	0.43	0.92	0.61	1.88	0.16	0.11	0.34
Max knee ab. mom (Nm/kg)	0.11	0.07	0.22	0.15	0.10	0.31	0.05	0.03	0.12	0.27	0.17	0.67	0.18	0.12	0.36	0.43	0.29	0.88
Max knee add. mom (Nm/kg)	0.17	0.11	0.34	0.15	0.10	0.30	0.12	0.08	0.29	0.06	0.04	0.15	0.36	0.24	0.73	0.28	0.18	0.57
Max knee ext. mom (Nm/kg)	0.05	0.04	0.11	0.46	0.30	0.93	0.02	0.02	0.06	0.52	0.32	1.27	0.09	0.06	0.17	0.74	0.49	1.50
Max knee int. mom (Nm/kg)	0.04	0.03	0.08	0.13	0.09	0.27	0.09	0.05	0.21	0.22	0.14	0.53	0.14	0.09	0.28	0.36	0.24	0.74
Mean	-	-	-	0.19	0.13	0.39	-	-	-	0.20	0.13	0.50	-	-	-	0.41	0.27	0.83
SD	-	-	-	0.12	0.08	0.24	-	-	-	0.16	0.10	0.38	-	-	-	0.20	0.13	0.39
<u>Stair ascent</u>																		
Max knee ext. mom (Nm/kg)	0.44	0.29	0.98	0.27	0.17	0.59	N/A	N/A	N/A	N/A	N/A	N/A	0.48	0.31	1.06	0.33	0.21	0.72
Max knee flx. mom (Nm/kg)	0.92	0.59	2.03	0.34	0.22	0.75	N/A	N/A	N/A	N/A	N/A	N/A	0.47	0.30	1.02	0.13	0.08	0.29
Knee flx at max ext. mom (°)	19.75	12.72	43.48	0.83	0.53	1.82	N/A	N/A	N/A	N/A	N/A	N/A	3.30	2.13	7.28	0.12	0.08	0.26
Knee flx at max flx. mom (°)	4.33	2.79	9.54	0.36	0.23	0.79	N/A	N/A	N/A	N/A	N/A	N/A	5.82	3.75	12.81	0.80	0.52	1.77
Max knee ab. mom (Nm/kg)	0.27	0.17	0.60	0.31	0.20	0.67	N/A	N/A	N/A	N/A	N/A	N/A	0.23	0.15	0.51	0.29	0.18	0.63
Max knee add. mom (Nm/kg)	0.37	0.24	0.80	0.35	0.22	0.76	N/A	N/A	N/A	N/A	N/A	N/A	0.37	0.24	0.82	0.25	0.16	0.55
Max knee ext. mom (Nm/kg)	0.13	0.08	0.28	0.25	0.16	0.54	N/A	N/A	N/A	N/A	N/A	N/A	0.08	0.05	0.17	0.19	0.12	0.42
Max knee int. mom (Nm/kg)	0.19	0.12	0.41	0.60	0.39	1.32	N/A	N/A	N/A	N/A	N/A	N/A	0.22	0.14	0.48	0.30	0.19	0.66
Mean	-	-	-	0.41	0.27	0.91	-	-	-	N/A	N/A	N/A	-	-	-	0.30	0.19	0.66
SD	-	-	-	0.20	0.13	0.44	-	-	-	N/A	N/A	N/A	-	-	-	0.22	0.14	0.48
<u>Stair descent</u>																		
Max knee ext. mom (Nm/kg)	0.48	0.29	1.38	0.26	0.16	0.75	0.44	0.26	1.27	0.39	0.23	1.11	0.44	0.29	0.90	0.53	0.35	1.08
Max knee flx. mom (Nm/kg)	0.27	0.16	0.77	0.06	0.04	0.18	0.67	0.40	1.94	0.12	0.07	0.33	0.57	0.38	1.15	0.29	0.19	0.60
Knee flx at max ext. mom (°)	3.99	2.39	11.48	0.86	0.52	2.48	5.22	3.13	15.00	0.72	0.43	2.07	3.89	2.57	7.91	0.53	0.35	1.08
Knee flx at max flx. mom (°)	10.22	6.12	29.35	0.66	0.40	1.91	8.48	5.08	24.37	0.40	0.24	1.16	12.72	8.41	25.89	0.78	0.51	1.58
Max knee ab. mom (Nm/kg)	0.44	0.26	1.25	0.56	0.34	1.61	0.24	0.14	0.68	0.16	0.10	0.46	0.20	0.13	0.40	0.57	0.37	1.15
Max knee add. mom (Nm/kg)	0.19	0.11	0.54	0.12	0.07	0.33	0.54	0.32	1.54	0.24	0.14	0.68	0.33	0.22	0.68	0.20	0.13	0.41
Max knee ext. mom (Nm/kg)	0.19	0.11	0.55	0.42	0.25	1.21	0.05	0.03	0.14	0.12	0.07	0.34	0.11	0.08	0.23	0.26	0.17	0.52
Max knee int. mom (Nm/kg)	0.08	0.05	0.23	0.33	0.20	0.94	0.10	0.06	0.29	0.34	0.21	0.99	0.19	0.12	0.38	0.33	0.22	0.67
Mean	-	-	-	0.41	0.25	1.18	-	-	-	0.31	0.19	0.89	-	-	-	0.44	0.29	0.89
SD	-	-	-	0.27	0.16	0.79	-	-	-	0.20	0.12	0.58	-	-	-	0.20	0.13	0.40

Appendix Y

Pearson's correlation coefficient *r* and the intraclass correlation of the knee kinetic parameters at three months post-surgery in Chapter 4

Table Appendix Y – Pearson’s correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee kinetic parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson’s *r*	95% CI		ICC	95% CI		Pearson’s *r*	95% CI		ICC	95% CI		Pearson’s *r*	95% CI		ICC	95% CI	
<u>Walking</u>																		
Max knee ext. mom (Nm/kg)	0.990	0.943	0.998	0.993	0.967	0.999	0.995	0.954	0.999	0.998	0.988	1.000	0.629	-0.136	0.924	0.692	0.047	0.930
Max knee flx. mom (Nm/kg)	0.992	0.952	0.999	0.995	0.974	0.999	0.998	0.980	1.000	0.999	0.995	1.000	0.953	0.755	0.992	0.965	0.837	0.993
Knee flx at max ext. mom (°)	0.962	0.799	0.993	0.975	0.882	0.995	0.965	0.705	0.996	0.973	0.824	0.996	0.811	0.248	0.964	0.861	0.457	0.971
Knee flx at max flx. mom (°)	0.935	0.675	0.988	0.957	0.802	0.991	0.973	0.769	0.997	0.989	0.922	0.998	0.973	0.853	0.995	0.983	0.919	0.997
Max knee ab. mom (Nm/kg)	0.987	0.927	0.998	0.986	0.933	0.997	0.932	0.495	0.993	0.970	0.802	0.996	0.814	0.256	0.965	0.869	0.480	0.972
Max knee add. mom (Nm/kg)	0.981	0.894	0.997	0.987	0.934	0.997	0.997	0.969	1.000	0.999	0.991	1.000	0.926	0.637	0.987	0.950	0.771	0.990
Max knee ext. mom (Nm/kg)	0.831	0.306	0.969	0.851	0.425	0.968	0.778	-0.090	0.974	0.844	0.248	0.977	0.457	-0.366	0.879	0.527	-0.214	0.883
Max knee int. mom (Nm/kg)	0.983	0.906	0.997	0.989	0.947	0.998	0.968	0.729	0.997	0.982	0.878	0.997	0.869	0.423	0.976	0.911	0.624	0.982
Mean	0.958	0.800	0.992	0.967	0.858	0.993	0.951	0.689	0.995	0.969	0.831	0.996	0.804	0.334	0.960	0.845	0.490	0.965
SD	0.055	0.220	0.010	0.048	0.184	0.010	0.073	0.356	0.009	0.052	0.247	0.008	0.178	0.426	0.040	0.158	0.395	0.039
<u>Stair ascent</u>																		
Max knee ext. mom (Nm/kg)	0.970	0.802	0.996	0.961	0.792	0.993	N/A	N/A	N/A	N/A	N/A	N/A	0.937	0.626	0.991	0.938	0.685	0.989
Max knee flx. mom (Nm/kg)	0.889	0.412	0.984	0.932	0.662	0.988	N/A	N/A	N/A	N/A	N/A	N/A	0.984	0.890	0.998	0.991	0.951	0.999
Knee flx at max ext. mom (°)	0.319	-0.571	0.864	0.388	-0.439	0.859	N/A	N/A	N/A	N/A	N/A	N/A	0.990	0.928	0.999	0.993	0.960	0.999
Knee flx at max flx. mom (°)	0.874	0.353	0.981	0.923	0.621	0.986	N/A	N/A	N/A	N/A	N/A	N/A	0.353	-0.545	0.874	0.430	-0.398	0.872
Max knee ab. mom (Nm/kg)	0.970	0.804	0.996	0.947	0.725	0.991	N/A	N/A	N/A	N/A	N/A	N/A	0.920	0.544	0.988	0.954	0.758	0.992
Max knee add. mom (Nm/kg)	0.902	0.465	0.986	0.929	0.648	0.987	N/A	N/A	N/A	N/A	N/A	N/A	0.941	0.645	0.991	0.965	0.814	0.994
Max knee ext. mom (Nm/kg)	0.951	0.699	0.993	0.967	0.821	0.994	N/A	N/A	N/A	N/A	N/A	N/A	0.964	0.768	0.995	0.981	0.893	0.997
Max knee int. mom (Nm/kg)	0.643	-0.213	0.941	0.734	0.057	0.949	N/A	N/A	N/A	N/A	N/A	N/A	0.923	0.555	0.989	0.949	0.735	0.991
Mean	0.815	0.344	0.968	0.848	0.486	0.968	N/A	N/A	N/A	N/A	N/A	N/A	0.877	0.551	0.978	0.900	0.675	0.979
SD	0.226	0.495	0.045	0.200	0.444	0.047	N/A	N/A	N/A	N/A	N/A	N/A	0.213	0.466	0.042	0.191	0.445	0.043
<u>Stair descent</u>																		
Max knee ext. mom (Nm/kg)	0.962	0.527	0.998	0.993	0.936	0.999	0.923	0.223	0.995	0.968	0.732	0.997	0.810	0.245	0.964	0.789	0.259	0.954
Max knee flx. mom (Nm/kg)	0.997	0.948	1.000	1.000	1.000	1.000	0.987	0.809	0.999	1.000	0.997	1.000	0.914	0.587	0.984	0.944	0.748	0.989
Knee flx at max ext. mom (°)	0.266	-0.805	0.930	0.371	-0.630	0.909	0.497	-0.686	0.959	0.668	-0.314	0.959	0.933	0.668	0.988	0.786	0.251	0.953
Knee flx at max flx. mom (°)	0.651	-0.543	0.974	0.750	-0.156	0.971	0.855	-0.110	0.990	0.962	0.690	0.996	0.445	-0.378	0.875	0.465	-0.292	0.864
Max knee ab. mom (Nm/kg)	0.955	0.460	0.997	0.867	0.187	0.985	0.991	0.860	0.999	0.999	0.991	1.000	0.731	0.054	0.948	0.752	0.171	0.945
Max knee add. mom (Nm/kg)	0.989	0.839	0.999	1.000	0.997	1.000	0.945	0.375	0.996	0.996	0.958	1.000	0.959	0.783	0.993	0.974	0.877	0.995
Max knee ext. mom (Nm/kg)	0.830	-0.194	0.988	0.955	0.639	0.995	0.993	0.896	1.000	1.000	0.997	1.000	0.936	0.682	0.989	0.958	0.808	0.992
Max knee int. mom (Nm/kg)	0.892	0.047	0.993	0.983	0.850	0.998	0.994	0.906	1.000	0.980	0.820	0.998	0.938	0.688	0.989	0.928	0.686	0.985
Mean	0.818	0.160	0.985	0.865	0.478	0.982	0.898	0.409	0.992	0.947	0.734	0.994	0.833	0.416	0.966	0.825	0.439	0.960
SD	0.250	0.640	0.024	0.218	0.613	0.031	0.169	0.580	0.014	0.114	0.441	0.014	0.175	0.408	0.040	0.170	0.407	0.043

Appendix Z

Typical error and standardised typical error of the knee kinetic parameters at nine months post-surgery in Chapter 4

Table Appendix Z – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee kinetic parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Walking																		
Max knee ext. mom (Nm/kg)	0.02	0.02	0.05	0.20	0.13	0.44	0.13	0.08	0.28	0.09	0.06	0.19	0.32	0.21	0.66	0.62	0.41	1.26
Max knee flx. mom (Nm/kg)	0.06	0.04	0.14	0.15	0.10	0.33	0.08	0.05	0.18	0.06	0.04	0.12	0.71	0.47	1.44	0.23	0.16	0.48
Knee flx at max ext. mom (°)	3.26	2.10	7.17	0.48	0.31	1.05	0.83	0.53	1.83	0.20	0.13	0.44	1.81	1.20	3.69	0.44	0.29	0.90
Knee flx at max flx. mom (°)	9.45	6.09	20.8	0.81	0.52	1.79	8.76	5.65	19.3	1.12	0.72	2.47	0.92	0.61	1.88	0.16	0.11	0.34
Max knee ab. mom (Nm/kg)	0.01	0.01	0.02	0.27	0.17	0.59	0.04	0.02	0.08	0.05	0.03	0.10	0.18	0.12	0.36	0.43	0.29	0.88
Max knee add. mom (Nm/kg)	0.01	0.01	0.02	0.13	0.08	0.28	0.09	0.06	0.19	0.17	0.11	0.38	0.36	0.24	0.73	0.28	0.18	0.57
Max knee ext. mom (Nm/kg)	0.00	0.00	0.01	0.32	0.21	0.71	0.01	0.01	0.03	0.25	0.16	0.55	0.09	0.06	0.17	0.74	0.49	1.50
Max knee int. mom (Nm/kg)	0.01	0.01	0.03	0.60	0.39	1.33	0.03	0.02	0.07	0.17	0.11	0.38	0.14	0.09	0.28	0.36	0.24	0.74
Mean	-	-	-	0.37	0.24	0.82	-	-	-	0.26	0.17	0.58	-	-	-	0.41	0.27	0.83
SD	-	-	-	0.24	0.16	0.53	-	-	-	0.35	0.23	0.78	-	-	-	0.20	0.13	0.39
Stair ascent																		
Max knee ext. mom (Nm/kg)	0.05	0.03	0.10	0.33	0.21	0.73	0.05	0.03	0.12	0.03	0.02	0.08	0.48	0.31	1.06	0.33	0.21	0.72
Max knee flx. mom (Nm/kg)	0.06	0.04	0.13	0.32	0.20	0.70	0.06	0.04	0.16	0.03	0.02	0.08	0.47	0.30	1.02	0.13	0.08	0.29
Knee flx at max ext. mom (°)	22.7	14.7	50.1	0.83	0.53	1.82	16.2	10.1	39.7	0.49	0.31	1.21	3.30	2.13	7.28	0.12	0.08	0.26
Knee flx at max flx. mom (°)	16.4	10.6	36.1	0.93	0.60	2.05	7.85	4.90	19.3	1.01	0.63	2.48	5.82	3.75	12.8	0.80	0.52	1.77
Max knee ab. mom (Nm/kg)	0.02	0.01	0.04	0.26	0.17	0.57	0.02	0.01	0.04	0.03	0.02	0.08	0.23	0.15	0.51	0.29	0.18	0.63
Max knee add. mom (Nm/kg)	0.05	0.03	0.12	0.31	0.20	0.69	0.05	0.03	0.11	0.19	0.12	0.47	0.37	0.24	0.82	0.25	0.16	0.55
Max knee ext. mom (Nm/kg)	0.01	0.01	0.02	0.16	0.10	0.34	0.01	0.01	0.03	0.07	0.05	0.18	0.08	0.05	0.17	0.19	0.12	0.42
Max knee int. mom (Nm/kg)	0.02	0.01	0.04	0.20	0.13	0.43	0.02	0.01	0.05	0.20	0.12	0.49	0.22	0.14	0.48	0.30	0.19	0.66
Mean	-	-	-	0.42	0.27	0.92	-	-	-	0.26	0.16	0.63	-	-	-	0.30	0.19	0.66
SD	-	-	-	0.29	0.19	0.65	-	-	-	0.34	0.21	0.84	-	-	-	0.22	0.14	0.48
Stair descent																		
Max knee ext. mom (Nm/kg)	0.05	0.03	0.14	0.15	0.09	0.44	0.08	0.05	0.19	0.08	0.05	0.19	0.44	0.29	0.90	0.53	0.35	1.08
Max knee flx. mom (Nm/kg)	0.05	0.03	0.14	0.15	0.09	0.44	0.03	0.02	0.08	0.01	0.01	0.03	0.57	0.38	1.15	0.29	0.19	0.60
Knee flx at max ext. mom (°)	3.04	1.82	8.72	0.80	0.48	2.31	2.19	1.37	5.37	0.59	0.37	1.45	3.89	2.57	7.91	0.53	0.35	1.08
Knee flx at max flx. mom (°)	14.9	8.92	42.8	0.96	0.57	2.75	13.7	8.53	33.5	0.63	0.39	1.54	12.7	8.41	25.9	0.78	0.51	1.58
Max knee ab. mom (Nm/kg)	0.02	0.01	0.05	0.08	0.05	0.24	0.18	0.11	0.45	0.18	0.11	0.44	0.20	0.13	0.40	0.57	0.37	1.15
Max knee add. mom (Nm/kg)	0.05	0.03	0.14	0.23	0.14	0.66	0.13	0.08	0.32	0.32	0.20	0.80	0.33	0.22	0.68	0.20	0.13	0.41
Max knee ext. mom (Nm/kg)	0.03	0.02	0.10	0.29	0.17	0.83	0.08	0.05	0.19	0.20	0.13	0.50	0.11	0.08	0.23	0.26	0.17	0.52
Max knee int. mom (Nm/kg)	0.02	0.01	0.06	0.61	0.36	1.74	0.04	0.02	0.09	0.37	0.23	0.90	0.19	0.12	0.38	0.33	0.22	0.67
Mean	-	-	-	0.41	0.24	1.18	-	-	-	0.30	0.19	0.73	-	-	-	0.44	0.29	0.89
SD	-	-	-	0.33	0.20	0.96	-	-	-	0.23	0.14	0.55	-	-	-	0.20	0.13	0.40

Appendix AA

Pearson's correlation coefficient *r* and the intraclass correlation of the knee kinetic parameters at nine months post-surgery in Chapter 4

Table Appendix AA – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee kinetic parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
<u>Walking</u>																		
Max knee ext. mom (Nm/kg)	0.970	0.808	0.996	0.979	0.884	0.996	1.000	0.999	1.000	0.996	0.978	0.999	0.629	-0.136	0.924	0.692	0.047	0.930
Max knee flx. mom (Nm/kg)	0.987	0.914	0.998	0.988	0.933	0.998	0.999	0.994	1.000	0.998	0.991	1.000	0.953	0.755	0.992	0.965	0.837	0.993
Knee flx at max ext. mom (°)	0.864	0.317	0.980	0.849	0.356	0.972	0.960	0.745	0.994	0.979	0.882	0.996	0.811	0.248	0.964	0.861	0.457	0.971
Knee flx at max flx. mom (°)	0.440	-0.468	0.896	0.413	-0.415	0.867	-0.309	-0.862	0.579	-0.316	-0.836	0.503	0.973	0.853	0.995	0.983	0.919	0.997
Max knee ab. mom (Nm/kg)	0.928	0.582	0.990	0.960	0.789	0.993	1.000	0.999	1.000	0.999	0.994	1.000	0.814	0.256	0.965	0.869	0.480	0.972
Max knee add. mom (Nm/kg)	0.984	0.893	0.998	0.992	0.954	0.999	0.998	0.985	1.000	0.985	0.913	0.997	0.926	0.637	0.987	0.950	0.771	0.990
Max knee ext. mom (Nm/kg)	0.909	0.493	0.987	0.939	0.693	0.989	0.964	0.772	0.995	0.966	0.818	0.994	0.457	-0.366	0.879	0.527	-0.214	0.883
Max knee int. mom (Nm/kg)	0.652	-0.198	0.942	0.732	0.053	0.948	0.994	0.957	0.999	0.984	0.911	0.997	0.869	0.423	0.976	0.911	0.624	0.982
Mean	0.842	0.418	0.973	0.857	0.531	0.970	0.826	0.699	0.946	0.824	0.706	0.936	0.804	0.334	0.960	0.845	0.490	0.965
SD	0.196	0.511	0.036	0.200	0.495	0.045	0.459	0.639	0.148	0.461	0.626	0.175	0.178	0.426	0.040	0.158	0.395	0.039
<u>Stair ascent</u>																		
Max knee ext. mom (Nm/kg)	0.963	0.762	0.995	0.936	0.679	0.989	1.000	0.996	1.000	1.000	0.997	1.000	0.937	0.626	0.991	0.938	0.685	0.989
Max knee flx. mom (Nm/kg)	0.974	0.830	0.996	0.943	0.708	0.990	1.000	0.996	1.000	1.000	0.997	1.000	0.984	0.890	0.998	0.991	0.951	0.999
Knee flx at max ext. mom (°)	0.319	-0.571	0.864	0.389	-0.438	0.860	0.765	-0.122	0.973	0.865	0.318	0.980	0.990	0.928	0.999	0.993	0.960	0.999
Knee flx at max flx. mom (°)	0.176	-0.665	0.820	0.170	-0.610	0.783	-0.025	-0.820	0.803	-0.026	-0.765	0.743	0.353	-0.545	0.874	0.430	-0.398	0.872
Max knee ab. mom (Nm/kg)	0.940	0.639	0.991	0.963	0.801	0.993	0.999	0.990	1.000	1.000	0.997	1.000	0.920	0.544	0.988	0.954	0.758	0.992
Max knee add. mom (Nm/kg)	0.903	0.470	0.986	0.944	0.714	0.990	0.975	0.783	0.997	0.986	0.907	0.998	0.941	0.645	0.991	0.965	0.814	0.994
Max knee ext. mom (Nm/kg)	0.989	0.922	0.998	0.987	0.929	0.998	0.995	0.954	0.999	0.998	0.987	1.000	0.964	0.768	0.995	0.981	0.893	0.997
Max knee int. mom (Nm/kg)	0.962	0.759	0.995	0.980	0.888	0.997	0.967	0.719	0.996	0.985	0.899	0.998	0.923	0.555	0.989	0.949	0.735	0.991
Mean	0.778	0.393	0.956	0.789	0.459	0.950	0.835	0.562	0.971	0.851	0.667	0.965	0.877	0.551	0.978	0.900	0.675	0.979
SD	0.331	0.639	0.071	0.320	0.615	0.082	0.356	0.672	0.068	0.357	0.623	0.090	0.213	0.466	0.042	0.191	0.445	0.043
<u>Stair descent</u>																		
Max knee ext. mom (Nm/kg)	0.989	0.842	0.999	0.999	0.992	1.000	1.000	0.996	1.000	0.998	0.985	1.000	0.810	0.245	0.964	0.789	0.259	0.954
Max knee flx. mom (Nm/kg)	0.995	0.929	1.000	0.999	0.992	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.914	0.587	0.984	0.944	0.748	0.989
Knee flx at max ext. mom (°)	0.467	-0.706	0.956	0.508	-0.516	0.934	0.722	-0.217	0.967	0.777	0.055	0.966	0.933	0.668	0.988	0.786	0.251	0.953
Knee flx at max flx. mom (°)	0.087	-0.861	0.900	0.130	-0.762	0.852	0.636	-0.362	0.955	0.734	-0.046	0.958	0.445	-0.378	0.875	0.465	-0.292	0.864
Max knee ab. mom (Nm/kg)	0.997	0.958	1.000	1.000	0.999	1.000	0.999	0.987	1.000	0.988	0.918	0.998	0.731	0.054	0.948	0.752	0.171	0.945
Max knee add. mom (Nm/kg)	0.989	0.835	0.999	0.996	0.961	1.000	0.958	0.660	0.996	0.954	0.713	0.993	0.959	0.783	0.993	0.974	0.877	0.995
Max knee ext. mom (Nm/kg)	0.952	0.434	0.997	0.990	0.905	0.999	0.990	0.912	0.999	0.985	0.895	0.998	0.936	0.682	0.989	0.958	0.808	0.992
Max knee int. mom (Nm/kg)	0.707	-0.466	0.979	0.824	0.037	0.980	0.874	0.216	0.986	0.937	0.624	0.991	0.938	0.688	0.989	0.928	0.686	0.985
Mean	0.773	0.246	0.979	0.806	0.451	0.971	0.897	0.524	0.988	0.922	0.643	0.988	0.833	0.416	0.966	0.825	0.439	0.960
SD	0.337	0.788	0.035	0.323	0.749	0.053	0.143	0.568	0.018	0.105	0.416	0.017	0.175	0.408	0.040	0.170	0.407	0.043

Appendix AB

Typical error and standardised typical error of the maximum knee angular velocity and loading ratio parameters at pre-surgery

Table Appendix AB – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee angular velocity and loading ratio parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
<u>Sit to stand</u>																		
Max knee ext velocity (°/s)	8.12	5.37	16.5	0.40	0.26	0.81	5.73	3.58	14.1	0.19	0.12	0.47	9.68	6.24	21.3	0.23	0.15	0.51
Loading ratio	0.09	0.06	0.18	0.59	0.39	1.19	0.05	0.03	0.11	0.21	0.13	0.52	0.07	0.04	0.15	0.28	0.18	0.61
Mean	-	-	-	0.50	0.33	1.00	-	-	-	0.20	0.13	0.50	-	-	-	0.26	0.17	0.56
SD	-	-	-	0.13	0.09	0.27	-	-	-	0.01	0.01	0.04	-	-	-	0.04	0.02	0.07
<u>Stand to sit</u>																		
Max knee flx velocity (°/s)	10.4	6.89	21.2	0.35	0.23	0.72	9.71	6.06	23.8	0.82	0.51	2.00	7.04	4.54	15.51	0.38	0.24	0.83
Loading ratio	0.07	0.05	0.14	0.32	0.21	0.66	0.11	0.07	0.27	0.52	0.33	1.28	0.13	0.08	0.29	0.88	0.57	1.95
Mean	-	-	-	0.34	0.22	0.69	-	-	-	0.67	0.42	1.64	-	-	-	0.63	0.41	1.39
SD	-	-	-	0.02	0.01	0.04	-	-	-	0.21	0.13	0.51	-	-	-	0.35	0.23	0.79

Appendix AC

Pearson's correlation coefficient *r* and the intraclass correlation of the maximum knee angular velocity and loading ratio parameters at pre-surgery

Table Appendix AC – Pearson’s correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee angular velocity and loading ratio parameters at the pre-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson’s *r*	95% CI		ICC	95% CI		Pearson’s *r*	95% CI		ICC	95% CI		Pearson’s *r*	95% CI		ICC	95% CI	
<u>Sit to stand</u>																		
Max knee ext velocity (°/s)	0.881	0.466	0.978	0.890	0.548	0.977	0.965	0.704	0.996	0.987	0.909	0.998	0.961	0.754	0.994	0.971	0.844	0.995
Loading ratio	0.682	-0.044	0.936	0.731	0.125	0.940	0.956	0.646	0.995	0.983	0.885	0.998	0.937	0.626	0.991	0.958	0.778	0.993
Mean	0.782	0.211	0.957	0.811	0.337	0.959	0.961	0.675	0.996	0.985	0.897	0.998	0.949	0.690	0.993	0.965	0.811	0.994
SD	0.141	0.361	0.030	0.112	0.299	0.026	0.006	0.041	0.001	0.003	0.017	0.000	0.017	0.091	0.002	0.009	0.047	0.001
<u>Stand to sit</u>																		
Max knee flx velocity (°/s)	0.911	0.576	0.984	0.916	0.642	0.983	0.337	-0.653	0.902	0.430	-0.480	0.894	0.858	0.297	0.979	0.914	0.584	0.985
Loading ratio	0.897	0.523	0.981	0.931	0.697	0.986	0.732	-0.197	0.968	0.840	0.235	0.976	0.600	-0.280	0.930	0.270	-0.540	0.820
Mean	0.904	0.550	0.983	0.924	0.670	0.985	0.535	-0.425	0.935	0.635	-0.123	0.935	0.729	0.008	0.955	0.592	0.022	0.903
SD	0.010	0.037	0.002	0.011	0.039	0.002	0.279	0.322	0.047	0.290	0.506	0.058	0.182	0.408	0.035	0.455	0.795	0.117

Appendix AD

Typical error and standardised typical error of the maximum knee angular velocity and loading ratio parameters at three months post-surgery

Table Appendix AD – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee angular velocity and loading ratio parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Sit to stand																		
Max knee ext velocity (°/s)	4.66	3.08	9.49	0.30	0.20	0.62	N/A	N/A	N/A	N/A	N/A	N/A	9.68	6.24	21.3	0.23	0.15	0.51
Loading ratio	0.15	0.10	0.30	0.88	0.58	1.79	N/A	N/A	N/A	N/A	N/A	N/A	0.07	0.04	0.15	0.28	0.18	0.61
Mean	-	-	-	0.59	0.39	1.21	N/A	N/A	N/A	N/A	N/A	N/A	-	-	-	0.26	0.17	0.56
SD	-	-	-	0.41	0.27	0.83	N/A	N/A	N/A	N/A	N/A	N/A	-	-	-	0.04	0.02	0.07
Stand to sit																		
Max knee flx velocity (°/s)	6.01	3.97	12.2	0.34	0.22	0.68	N/A	N/A	N/A	N/A	N/A	N/A	7.04	4.54	15.5	0.38	0.24	0.83
Loading ratio	0.15	0.10	0.31	0.81	0.53	1.64	N/A	N/A	N/A	N/A	N/A	N/A	0.13	0.08	0.29	0.88	0.57	1.95
Mean	-	-	-	0.58	0.38	1.16	N/A	N/A	N/A	N/A	N/A	N/A	-	-	-	0.63	0.41	1.39
SD	-	-	-	0.33	0.22	0.68	N/A	N/A	N/A	N/A	N/A	N/A	-	-	-	0.35	0.23	0.79

Appendix AE

Pearson's correlation coefficient *r* and the intraclass correlation of the maximum knee angular velocity and loading ratio parameters at three months post-surgery

Table Appendix AE – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee angular velocity and loading ratio parameters at the three months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
<u>Sit to stand</u>																		
Max knee ext velocity (°/s)	0.963	0.802	0.993	0.940	0.732	0.988	N/A	N/A	N/A	N/A	N/A	N/A	0.961	0.754	0.994	0.971	0.844	0.995
Loading ratio	0.264	-0.541	0.817	0.273	-0.480	0.795	N/A	N/A	N/A	N/A	N/A	N/A	0.937	0.626	0.991	0.958	0.778	0.993
Mean	0.614	0.131	0.905	0.607	0.126	0.892	N/A	N/A	N/A	N/A	N/A	N/A	0.949	0.690	0.993	0.965	0.811	0.994
SD	0.494	0.950	0.124	0.472	0.857	0.136	N/A	N/A	N/A	N/A	N/A	N/A	0.017	0.091	0.002	0.009	0.047	0.001
<u>Stand to sit</u>																		
Max knee flx velocity (°/s)	0.888	0.488	0.980	0.925	0.675	0.985	N/A	N/A	N/A	N/A	N/A	N/A	0.858	0.297	0.979	0.914	0.584	0.985
Loading ratio	0.352	-0.469	0.847	0.413	-0.349	0.846	N/A	N/A	N/A	N/A	N/A	N/A	0.600	-0.280	0.930	0.270	-0.540	0.820
Mean	0.620	0.010	0.914	0.669	0.163	0.916	N/A	N/A	N/A	N/A	N/A	N/A	0.729	0.008	0.955	0.592	0.022	0.903
SD	0.379	0.677	0.094	0.362	0.724	0.098	N/A	N/A	N/A	N/A	N/A	N/A	0.182	0.408	0.035	0.455	0.795	0.117

Appendix AF

Typical error and standardised typical error of the maximum knee angular velocity and loading ratio parameters at nine months post-surgery

Table Appendix AF – Typical error (TE) and standardised typical error (STE) of the between-trial reliability of knee angular velocity and loading ratio parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]

	Fixed Bearing						Mobile Bearing						Control					
	TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI		TE	95% CI		STE	95% CI	
Sit to stand																		
Max knee ext velocity (°/s)	10.1	6.51	22.2	0.47	0.30	1.02	15.3	9.86	33.7	0.22	0.14	0.48	9.68	6.24	21.3	0.23	0.15	0.51
Loading ratio	0.10	0.06	0.24	0.50	0.31	1.22	0.14	0.09	0.31	0.37	0.24	0.82	0.07	0.04	0.15	0.28	0.18	0.61
Mean	-	-	-	0.49	0.31	1.12	-	-	-	0.30	0.19	0.65	-	-	-	0.26	0.17	0.56
SD	-	-	-	0.02	0.01	0.14	-	-	-	0.11	0.07	0.24	-	-	-	0.04	0.02	0.07
Stand to sit																		
Max knee flx velocity (°/s)	13.2	8.49	29.0	0.35	0.22	0.77	11.7	7.53	25.8	0.61	0.40	1.35	7.04	4.54	15.5	0.38	0.24	0.83
Loading ratio	0.16	0.10	0.36	0.83	0.54	1.83	0.07	0.04	0.15	0.25	0.16	0.55	0.13	0.08	0.29	0.88	0.57	1.95
Mean	-	-	-	0.59	0.38	1.30	-	-	-	0.43	0.28	0.95	-	-	-	0.63	0.41	1.39
SD	-	-	-	0.34	0.23	0.75	-	-	-	0.25	0.17	0.57	-	-	-	0.35	0.23	0.79

Appendix AG

Pearson's correlation coefficient *r* and the intraclass correlation of the maximum knee angular velocity and loading ratio parameters at nine months post-surgery

Table Appendix AG – Pearson's correlation coefficient *r* and the intraclass correlation (ICC) for the correlation of knee angular velocity and loading ratio parameters at the nine months post-surgery time point in fixed bearing (FB), mobile bearing (MB), and control participants. ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Fixed Bearing						Mobile Bearing						Control					
	Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
<u>Sit to stand</u>																		
Max knee ext velocity (°/s)	0.806	0.135	0.970	0.859	0.388	0.974	0.960	0.750	0.994	0.974	0.859	0.996	0.961	0.754	0.994	0.971	0.844	0.995
Loading ratio	0.752	-0.153	0.971	0.861	0.304	0.979	0.867	0.328	0.980	0.918	0.600	0.985	0.937	0.626	0.991	0.958	0.778	0.993
Mean	0.779	-0.009	0.971	0.860	0.346	0.977	0.914	0.539	0.987	0.946	0.730	0.991	0.949	0.690	0.993	0.965	0.811	0.994
SD	0.038	0.204	0.001	0.001	0.059	0.004	0.066	0.298	0.010	0.040	0.183	0.008	0.017	0.091	0.002	0.009	0.047	0.001
<u>Stand to sit</u>																		
Max knee flx velocity (°/s)	0.944	0.662	0.992	0.929	0.645	0.987	0.687	-0.137	0.949	0.718	0.024	0.945	0.858	0.297	0.979	0.914	0.584	0.985
Loading ratio	0.333	-0.561	0.868	0.380	-0.447	0.857	0.956	0.727	0.994	0.966	0.818	0.994	0.600	-0.280	0.930	0.270	-0.540	0.820
Mean	0.639	0.051	0.930	0.655	0.099	0.922	0.822	0.295	0.972	0.842	0.421	0.970	0.729	0.008	0.955	0.592	0.022	0.903
SD	0.432	0.865	0.088	0.388	0.772	0.092	0.190	0.611	0.032	0.175	0.561	0.035	0.182	0.408	0.035	0.455	0.795	0.117

Appendix AJ

Typical error, standardised typical error, Pearson's correlation coefficient *r*, and the intraclass correlation of the between-session knee kinematic variables

Table Appendix AJ – Typical error (TE), standardised typical error (STE), Pearson's correlation coefficient *r*, and the intraclass correlation (ICC) for the assessment of between-session reliability in control participants. A modified Cohen scale gives interpretation of the magnitude of the STE. STE<0.2 = trivial; 0.2≤STE<0.6 = small; 0.6≤STE<1.2 = moderate; 1.2≤STE<2 = large; STE≥2 = very large [157]; ICC<0.5 = poor; 0.5≤ICC<0.75 = moderate; ICC ≥0.75 = good [172]

	Control											
	TE	95% CI		STE	95% CI		Pearson's *r*	95% CI		ICC	95% CI	
Walking												
Min knee flexion (°)	0.96	0.63	1.95	0.80	0.53	1.63	0.37	-0.45	0.85	0.42	-0.34	0.85
Max knee flexion (°)	0.97	0.64	1.97	0.29	0.19	0.59	0.92	0.60	0.99	0.95	0.76	0.99
Sagittal knee ROM (°)	1.37	0.91	2.80	0.49	0.32	1.00	0.78	0.18	0.96	0.82	0.35	0.96
Max knee abduction (°)	0.70	0.47	1.43	0.10	0.07	0.20	0.99	0.95	1.00	0.99	0.97	1.00
Max knee adduction (°)	2.07	1.37	4.22	0.27	0.18	0.56	0.92	0.63	0.99	0.95	0.78	0.99
Frontal knee ROM (°)	2.25	1.48	4.57	0.32	0.21	0.64	0.90	0.54	0.98	0.93	0.71	0.99
Max knee ext. rot. (°)	3.82	2.53	7.78	0.47	0.31	0.95	0.78	0.18	0.96	0.84	0.41	0.97
Max knee int. rot. (°)	3.54	2.34	7.21	0.44	0.29	0.90	0.80	0.23	0.96	0.86	0.45	0.97
Axial knee ROM (°)	1.78	1.18	3.63	0.51	0.34	1.04	0.78	0.16	0.96	0.80	0.30	0.96
Mean	1.94	1.28	3.95	0.41	0.27	0.84	0.81	0.33	0.96	0.84	0.49	0.96
SD	1.12	0.74	2.28	0.20	0.13	0.40	0.18	0.40	0.04	0.17	0.39	0.05
Stair ascent												
Min knee flexion (°)	1.80	1.19	3.66	0.42	0.28	0.86	0.82	0.28	0.97	0.88	0.50	0.97
Max knee flexion (°)	1.42	0.94	2.89	0.40	0.27	0.82	0.84	0.34	0.97	0.89	0.54	0.98
Sagittal knee ROM (°)	2.25	1.49	4.59	0.38	0.25	0.78	0.86	0.40	0.97	0.90	0.58	0.98
Max knee abduction (°)	2.50	1.65	5.09	0.39	0.26	0.79	0.85	0.37	0.97	0.90	0.57	0.98
Max knee adduction (°)	4.18	2.76	8.51	0.36	0.24	0.74	0.87	0.43	0.98	0.91	0.62	0.98
Frontal knee ROM (°)	2.65	1.75	5.40	0.43	0.28	0.87	0.82	0.27	0.97	0.87	0.49	0.97
Max knee ext. rot. (°)	7.39	4.88	15.0	0.82	0.54	1.66	0.34	-0.48	0.84	0.39	-0.37	0.84
Max knee int. rot. (°)	8.89	5.88	18.1	0.90	0.60	1.84	0.18	-0.60	0.79	0.22	-0.53	0.77
Axial knee ROM (°)	2.71	1.79	5.51	0.48	0.32	0.99	0.77	0.14	0.96	0.83	0.36	0.96
Mean	3.75	2.48	7.64	0.51	0.34	1.04	0.71	0.13	0.93	0.75	0.31	0.94
SD	2.63	1.74	5.35	0.20	0.13	0.41	0.26	0.39	0.07	0.26	0.44	0.08
Stair descent												
Min knee flexion (°)	1.26	0.83	2.56	0.34	0.22	0.68	0.89	0.49	0.98	0.93	0.68	0.98
Max knee flexion (°)	0.89	0.59	1.81	0.22	0.14	0.44	0.95	0.76	0.99	0.97	0.86	0.99
Sagittal knee ROM (°)	1.31	0.87	2.68	0.24	0.16	0.49	0.94	0.71	0.99	0.96	0.83	0.99
Max knee abduction (°)	2.53	1.67	5.15	0.43	0.29	0.88	0.82	0.28	0.97	0.87	0.48	0.97
Max knee adduction (°)	2.82	1.86	5.73	0.38	0.25	0.77	0.86	0.39	0.97	0.90	0.59	0.98
Frontal knee ROM (°)	1.75	1.16	3.57	0.33	0.22	0.68	0.89	0.50	0.98	0.93	0.68	0.98
Max knee ext. rot. (°)	3.63	2.40	7.38	0.55	0.36	1.12	0.71	0.00	0.94	0.77	0.21	0.95
Max knee int. rot. (°)	3.40	2.25	6.92	0.52	0.34	1.06	0.73	0.05	0.95	0.80	0.28	0.96
Axial knee ROM (°)	2.68	1.77	5.46	0.56	0.37	1.13	0.69	-0.03	0.94	0.76	0.19	0.95
Mean	2.25	1.49	4.59	0.40	0.26	0.81	0.83	0.35	0.97	0.88	0.53	0.97
SD	0.98	0.65	2.00	0.13	0.08	0.26	0.10	0.29	0.02	0.08	0.26	0.02

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